THE CHEMISTRY AND HYDROGRAPHY OF SOME TROPICAL COASTAL LAGOONS - PACIFIC COAST OF MEXICO

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Summary

A comprehensive review was made of the processes controlling the geology, hydrography and chemistry of coastal lagoons.

The lagoons selected for study are along the Pacific coast of Guerrero, Mexico. On the basis of preliminary examination of lagoon type, the Lagunas Chautengo, Apozahualco and Mitla were chosen for detailed examination.

Parameters considered in the present study were; depth, Secchi depth, salinity, temperature, oxygen, alkalinity, pH, dissolved nutrients and phytoplankton pigments. General surveys were conducted on a seasonal basis in the Lagunas Chautengo and Apozahualco and 24 hour studies were made in the Laguna Mitla. In addition, two methods for measuring primary productivity were examined and applied to the Lagunas Mitla and Chautengo. Studies of carbon, nitrogen and phosphorus were also conducted on sediment samples from these lagoons.

For each of the lagoons, the overall seasonal variations in the hydrography and chemistry were investigated and described. For each of the surveys in the Laguna Chautengo, the distribution of salinity was investigated and the presence of stratification examined. From this, a general distribution of water masses was proposed.

Data on the surface distribution of chemical parameters, productivity and diurnal variations, was used to illustrate the process of eutrophication in the lagoons studied. From the diurnal variations in the Laguna Mitla, the nature and magnitude of nutrient regeneration was illustrated and its importance in maintaining the high productivity was discussed.

Finally, the results of sediment analyses were presented and the core analyses from Mitla used to illustrate how the pattern of eutrophication may have changed during the history of the lagoon.

CONTENTS

LIST OF FIGURES

Chapter 1.

Chapter 2.

Chapter 3.

Chapter 5.

Chapter 6.

LIST OF TABLES

Chapter 2.

Chapter 4.

Chapter 5.

Chapter 6.

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1. COASTAL LAGOONS : AN INTRODUCTION

Economically important areas of saline water exist on both sides of the coastal margin; the continental shelf and open bays on one hand, and semi-enclosed saline waters (lagoons, estuaries and fjords) on the other. In most temperate regions each of these areas is of economic importance to the coastal state. However, in the case of many tropical and subtropical regions, the inherently low production of the near-shore environment, coupled with the limited amount of continental shelf, highlights still further the importance of "continental" marine environments.

The satisfactory definitions of "coastal lagoons" and "estuaries" have led to considerable difficulties since examples of both features were formed by similar mechanisms, though often showing somewhat different morphology and hydrography. Perhaps one possible solution to this problem would be to consider all "lagoons" and "estuaries" within a general classification of "partially enclosed saline waters". Historically the term lagoon is derived from the latin lacuna (an expression covering all isolated basins of water) and is now regarded, in English, to mean "a salt water lake parted by the sea by a sand-bank or enclosed by an atoll" (Oxford dictionary). In other languages (French - lagune, Spanish/Italian - laguna) it still preserves its latin meaning, thus causing ambiguities in translations. The problem is by no means resolved in scientific literature. Whereas Pritchard (1967) prefers to consider coastal lagoons as estuaries, Lankford (1976) groups many estuaries into his definition of a coastal lagoon :- "a coastal zone depression below M.H.H.W., having permanent or ephemeral communication with the sea, but protected from the sea by some type of barrier". The description of Emery and Stevenson (1958) is narrower in concept, lagoons being "bodies of water separated in most cases from the ocean by offshore bars or islands of marine origin and are usually parallel to the coastline."

Lagoons thus defined form a very important shoreline feature associated with oceans, seas and even large lakes. For example, according to Phleger (1969) more than half the eastern side of the United States, south of New York, and at least a third of the coasts of Mexico, are occupied by saline coastal lagoons. Economically, coastal lagoons are very important, supporting sheltered fisheries, recreational areas and harbours (such as those of Alexandria, Egypt; Miami, U.S.A; Venice, Italy and Lagos, Nigeria). Understanding and management of this environment is thus of increasing importance.

Published literature concerning coastal lagoons is widely dispersed and inaccessible. This chapter is, therefore, devoted to providing a brief review of the existing information on coastal lagoons.

1.1 Formation

The fundamental process leading to the formation of a coastal lagoon is a relative change in sea level, either by coastal emergence or submergence (Zenkovitch 1969). According to Zenkovitch the initial formation of an offshore bar depends on two basic processes :-

(i) Sufficient transport and deposition of building material (shells, sand or pebbles) into the zone of wave action, and

(ii) that the offshore, submerged beach is less inclined than the equilibrium profile for the depositing sediment.

In the case of an emergent coastline, bar formation follows effective shallowing of the water overlying the offshore submerged beach. In that of a submergent coastline, one of two major mechanisms may operate :- A gradual sea level rise across a gently sloping coastal plain may initiate the formation of an offshore bar which sometimes migrates towards the new coast as the sea level continues to rise (Zenkovitch 1969) or with a more steeply sloping coast, the rising sea level may fill coastal depressions, a process which, under certain circumstances, may be followed by bar formation enclosing the depressions as lagoons (Lankford 1977). In the first case a continued rise of sea level may similarly fill coastal depressions enclosing coastal lagoons. Slowing or arrest of the sea-level change may lead to an offshore bar enclosing what is strictly referred to as a "bay" rather than a "lagoon" though it is convenient to consider the two forms together as "coastal lagoons".

Though evidence from foraminiferal assemblages indicates the presence of many generations of "fossil lagoons" (Walton and Smith 1969) many of the present day lagoons had their barriers formed in the Holocene sea level rise, 6000 - 7000 years B.P. (before present), (Curray et al 1969, Emery and Stevenson 1958, McIntire and Ho 1969, Phleger 1969, Zenkovitch 1969). The rate of rise of sea level during the late Holocene was about 15-20 cm in 100 years and so bar formation was often a gradual process, (Phleger 1969). The nature of bars formed depended on the abundance of building material. For example irregular supply of building material often led to the formation of multiple bar ridges (McIntire and Ho 1969); as in the case of Nayarit, Mexico, where a coastal plain 15 km wide and consisting of about 280 roughly parallel ridges was formed (Curray et al 1969) Longshore drift and coastal morphology determined the initial length of offshore bars (Zenkovitch 1969), the number of inlets being determined by the amount of water exchanged between the open ocean and the enclosed sea (mostly river flow where there is a small tidal range) (Phleger 1969).

Once an offshore bar has been established the processes of infilling begins to take place, passing through a stage where the lagoon is filled with marsh and finally ending with gradual landward migration of the bar over the marsh until the lagoon is eroded away (Johnson 1919, cited Emery and Stevenson 1958). The initial stages of the ageing process depend largely on the geological environment - for example the degree of isolation and the number and type of river inputs. Fragmentation of the lagoon by sedimentation typically takes place at null tidal points or by the invasion of a river delta (Phleger 1969, Bouma and Bryant 1969). Further encroachment of land takes place by wind transport of sand and in tropical conditions by the growth of mangrove swamps.

1.2 Sedimentary Processes

The state of maturity of a lagoon system depends on the extent to which the various interacting sedimentary processes have acted and the balance between the rates of sediment deposition and erosion and transport to the sea. The major sedimentary processes may be summarised as follows :-

1.2.1 River transport of sediments

Except for particularly arid areas, the bulk of sediments in coastal lagoons are contributed by rivers (Emery and Stevenson 1958b). On discharge into the lagoons, deposition of the larger size fractions of sediments generally forms a delta (Phleger 1969). These fractions frequently include wood debris and the sediments are occasionally laminated, especially in areas with irregular river flow (Shepard and Rusnak 1957). Delta growth is generally rapid (for example 0.3 miles/100 years - Shepard and Moore 1960) and occasionally spectacular, dividing an entire lagoon in less than half a century (Bouma and Bryant 1969).

1.2.2 Sea transported sediments

Sea transport of sediments into the lagoon environment generally depends on the tidal and wave regimes operating across the bar (Emery and Stevenson 1958, Phleger 1969). Where there is reciprocal tidal flow a sandy inlet delta may develop on both the seaward and landward sides of the inlet, sedimentation being provoked by the abrupt change in current velocity either side of the narrow inlet channel (Phleger 1969). This in turn, often leads to the development of a low island in the lagoon opposite the inlet channel.

Longshore drift of sediments is one of the most important factors controlling the form a lagoon takes and the nature of its inlet to the sea. Changes in the equilibrium between the scouring action of the currents flowing seawards across the inlet (tidal currents and/or river run off), and the depositional action of long-shore drift and wave transported sediments (reinforcing the bar), in extreme cases produces lagoons seasonally opening and closing to the sea (Lankford 1977, Warme 1969, Lawson 1966). These changes are particularly pronounced in areas where seasonal rains produce a large variability in river inputs.

A second effect of longshore drift is to promote migration of the inlet in the direction of the prevailing longshore drift (Phleger 1969). This migration has been measured in the Guerrero Negro lagoon (Mexico) as 200 metres in three years (Phleger 1969) and in the Mugu lagoon (California) as 1000 metres in 100 years with an annual cyclic migration of 200 metres (Warme 1969).

1.2.3 Wind transported sediments

Wind transport of solid material, particularly dune sand, is often a significant sedimentary process, particularly in arid zones (Phleger 1969). Where strong tidal currents exist, much of the fresh sand blown into the lagoon is transported out to sea by the strong ebb tides and much of this sand is probably re-deposited on the lagoon bar (Phleger 1969, Postma 1965). Wind-blown sand is particularly important in the lagoons fringing the Arabian desert where a wide coastal plain has been extending seawards over the past 4000 years (Evans and Bush 1969).

1.2.4 Processes affecting sediment distribution within lagoons

Probably the most important sedimentary effects taking place within lagoons are as a result of water transport of resuspended sediments and of biological processes. After the initial input of sediments into the system, sediment re-sorting occurs due to re-suspension by current and wave action and subsequent deposition. Thus it has been generally observed that the coarsest lagoon sediments often occur at the entrance channel to the sea where the tidal currents are the strongest (Emery and Stevenson 1958b, Phleger 1969). Where strong tidal currents exist, well-cut channels cross the lagoon (Phleger and Ewing 1962). Away from regions of strong current regimes, re-suspension of sediments by the action of wind-generated waves becomes very significant, providing that the depth of the water column is not greater than one half of the length of the incident waves (Shepard and Moore 1960). Postma (1965 found that the suspended material in the Guerrero Negro lagoon (Mexico) consisted mainly of suspended sand, phyto-plankton and material larger than 0.035 mm (probably conglomerates of clays and organic material). The finest of such fractions is often deposited in the zones farthest away from the tidal inlet (Postma 1965, Phleger 1969) and in basins where the water depth is greater than 5 metres (Emery and Stevenson 1958b). Additionally clay flocculation may occur in some specific areas where high ionic strength seawater mixes with river water (Phleger 1969).

Biological processes are generally important factors in determining the final composition of the lagoon sediments. For example, oyster reefs commonly build up and stabilise lagoon beds. Shepard and Rusnak (1957) report oyster beds cored to a depth of 12 metres in Texas lagoons. Calcium carbonate derived from shell debris may account for up to 47% of the sediment dry weight in tropical regions though only up to 6% in temperate or arctic areas (Emery and Stevenson 1958b). Similarly, organic detritus often forms an important constituent of lagoon surface sediments.

Biological factors may often determine the pattern of sediment deposition in a lagoon. For example, sea-grasses help to bind sediments and prevent erosion (Wood et al 1969) and mangroves are important in tropical zones for soil fixation and the establishment of new land areas (Lugo and Snedaker 1974, Kuenzler 1974). Furthermore, ammonifying bacteria associated with algal mats can promote the direct precipitation of calcium carbonate grains (Dalrymple 1965).

One further process which may have a considerable effect on sedimentation patterns is in the violent change due to storms and hurricanes, as shown by observations on the Texas lagoons after "Hurricane Carla" (Oppenheimer 1963) and "Hurricane Beulah" (Scott et al 1969). Both hurricanes resulted in a considerable redistribution and loss of sediments, the muddy water from the lagoon during "Hurricane Carla" being traced 3-4 miles out to sea. During "Hurricane Beulah", the lagoon barriers were breached at several points and course-grain sediments washed into areas of little tide or wave action within the lagoon, where they remain covering the former fine-grain surface sediments and detritus.

Each of the various processes outlined above contribute to the state of maturity of a lagoon. The rate of infilling of lagoon systems in Texas (U.S.A), has been extensively studied by Shepard and Moore (1960) using over 100 years of bathymetric data, together with ^{14}C dating of core samples. The average shoaling rate was found to be about 38 cm/century with a range of from 7 cm/century in isolated bays to 107 cm/century near river inputs. Using this data it was possible to predict that given present sedimentary conditions, it would take only a further 1000 years to completely fill the lagoon system with sediments. This amply illustrates the dynamic nature of the lagoon environment and the consequences of any control of river sediment inputs.

1.3 Physical Processes

In almost every aspect of the geology, chemistry and biology of coastal lagoons, a tremendous influence is exerted by the physical processes of mixing and circulation. For detailed considerations of these processes the reviews of Bowden (1967) and Groen (1969) should be consulted. A general outline of some of the most important features is given below.

Perhaps the most important factor determining the hydrography and hence the ecology of a lagoon is the relationship between the fresh water input into the system and the rate of evaporation. Where input (run-off) exceeds evaporation an "estuarine" circulatory pattern develops (Emery and Stevenson 1958, Groen 1969), that is to say there is a surface outflow of water of low salinity and a subsurface inflow of seawater.

The exact nature of this pattern may be considerably modified by the local tidal regime but generally yields the same resultant flow and gives rise to a lagoon having a mean salinity rather lower than that of the sea. In cases where evaporation exceeds the fresh water input, an "anti-estuarine" circulation develops with a surface inflow of seawater and a sub-surface outflow of higher salinity water. In these cases the lagoon salinity is generally higher than that of the sea and the lagoon may be classified as "hypersaline" (Emery and Stevenson 1958, Groen 1969).

Within the lagoon, circulation may be modified by the following factors :-

(a) Tides

The tidal influence on a lagoon is largely controlled by the size of the lagoon, the tidal range and the morphology of the inlet of the lagoon to the sea. A small inlet may cause strong damping of the tide and a shallow lagoon may considerably modify the harmonic pattern of the incident tide, especially where the travel time for the incident tidal wave is large compared with its period (Green 1969). In the case of lagoons with deep channels and a large tidal range the tide may be observed in all parts of the lagoon, as in the case of the Ojo de Liebre area of Baja California, Mexico (Phleger and Ewing 1962). With lagoons receiving a large run-off and having a small tidal range, the inflowing tide may be completely supressed, leading to very low salinity conditions (Phleger 1969).

(b) Winds

Winds can exert a considerable influence on the pattern of circulation within a lagoon. A steady wind stress may tend to pile up water at one side of a lagoon, sufficiently to cause periodic flooding of mud flats (Copeland *et al* 1966). In cases where there is a marked equilibrium slope of the water surface due to this effect, a circulation pattern may develop, having counter currents where the water is sufficiently deep to overcome horizontal friction (Groen 1969).

(c) Stratification

In certain cases, vertical mixing effects may be overcome and give way to a stratified water column. This effect has been reported in Californian lagoons (Carpelan 1969, Postma 1965) and in Nigeria (Hill and Webb 1958) but apparently not extensively studied.

Very few practical studies of lagoon circulation have been reported. A study by Zeigler (1969) used various drifters, consisting of flares, dye and drogues and suggested that the flow pattern observed probably consisted of a number of separate wind driven cells.

The mean salinity of a lagoon is generally determined by the run-off of fresh water into it (Groen 1969, Hill and Webb 1958, Okuda 1969, Dawson 1955). When considering the concentration of dissolved and suspended material in a lagoon, an important physical factor is the flushing time - an expression usefully embracing all the mixing and dilution processes controlling the exchange between lagoon and sea water (Groen 1969). Very few values of flushing time have been published owing to the practical difficulties of its estimation. Published values vary from a few days to several months (Posner 1959, Hela <u>et al</u> 1957, Postma 1965) and values of the order of years are probable in some isolated lagoons.

1.4 Chemical Processes

A coastal lagoon provides the site for a large variety of chemical interactions to take place. These include interactions within, and between the three reservoirs of materials present; the dissolved reservoir, the suspended particulates and the lagoon sediments. Such chemical interactions are generally mediated by geochemical or biochemical processes and often a combination of both.

The present state of knowledge regarding geochemical processes in coastal lagoons appears to be very limited. It would be anticipated that the geochemistry of a lagoon having estuarine circulation should be rather similar to that of an estuary but there is little published evidence to illustrate this hypothesis. In the case of a hypersaline lagoon, where the rate of evaporation is high, compositional changes are effected by precipitation of major and minor ions. Change in chemical equilibria including gas solubilities are also observed from changes in ionic strength and composition. For example, in the carbonate system the non-linearity of the relationship between salinity and alkalinity results from successive precipitation of carbonates and borates (Copeland 1967) with increasing salinity, an effect which by precipitation of calcium carbonate, also selectively removes some calcium from the system.

Biochemical processes have generally been much better studied than purely geochemical ones. Much of the published literature regarding chemical processes in lagoons has been concerned with dissolved and suspended nutrients, organic matter and the biochemistry of primary production. The present review will consider the state of knowledge of these biochemical and biogeochemical processes and, where possible consider their wider applications to the general chemistry of a lagoon.

For the present consideration, a lagoon will be regarded as a basin having overall chemical inputs and losses and in which a variety of internal processes are acting.

1.4.1 External sources

The supply of dissolved and particulate materials to a coastal lagoon depends upon the external reservoir of the materials and the availability of a transport mechanism to carry them into the lagoon.

In the case of dissolved and particulate nutrients (particulate organic carbon, nitrogen and phosphorus, and probably dissolved organic substances and trace metals, the principal source of materials is from continental reservoirs, mobilised by weathering, biological processes and human activities (such as in agriculture, industry and domestic activities) and transported during run-off. In certain cases, which will be discussed later, the sea may also provide a significant supply of materials.

The supply of nutrients by river transport can easily be observed from the increased concentration of these substances towards river discharges (Emery and Stevenson 1958), indeed in some cases (e.g. Howmiller and Weiner 1968) it can be clearly seen that the phytoplankton bloom within a lagoon may be directly supported and regulated by the rate of river input of nutrients. Conversely, a lack of river input or a depleted continental nutrient reservoir may lead to a lagoon having a low primary productivity (Tampi 1969). A comparison by Okuda (1969), of two morphologically similar lagoons receiving respectively seasonal and continuous river run-off showed the importance of a steady input of river water in maintaining a stable lagoon ecosystem.

The form in which a river discharges into a lagoon is often of importance to the resulting system. For example, in the case of a river flowing into a lagoon having an estuarine circulation, (i.e. surface outflow of brackish water and subsurface inflow of sea water) a "sediment trap" may develop where sediments falling through the water column are carried river-wards by the sea water inflow (Postma 1969). Thus the fine river-borne sediments and detritus may be retained in the vicinity of the river discharge into the lagoon, often resulting in an area of localised high nutrient regeneration. High nutrient inputs may also result from rivers passing through dense mangrove swamps as in the case of the "Marigots" of Brasil (Kato 1966).

When considering the run-off into a lagoon, it is often necessary to consider the effect of direct rainfall. According to Collier and Hedgpeth (1950), in their discussion of the lagoons of Texas, such water bodies may receive as much as sixty times their volume in rain water in any one year. Whilst the effect of such an input is generally to "dilute" the lagoon by flushing, the rain may carry an appreciable quantity of nutrients, sufficient to cause eutophication of estuarine waters (Reinhold and Daiker 1967).

Despite the emphasis on lagoon systems having river inputs or direct run-off, there are many examples of lagoons dominated by evaporation and having an average salinity rather higher than that of the adjacent sea water. These hypersaline lagoons fall into two general classes, those with a permanent sea connection and an anti-estuarine circulation, and "evaporation basins" - lagoons having an ephemeral sea connection and a period of intense evaporation. It is evident from the many studies of hypersaline systems (e.g. Copeland 1967, Copeland and Nixon 1974, Nichols 1966, Postma 1969) that the total concentration of dissolved and particulate nutrients within such a system is generally considerably higher than that of the adjacent sea.

This effect generally results from long-term retention of irregularly introduced nutrients (from run-off) together with a removal or concentration of nutrient material from sea water. In a large evaporating basin such as the Mexican Laguna Madre which has been reported as attaining salinity $295^{\circ}/_{oo}$ after five years isolation (Copeland 1967) or that of the Venezuelar Laguna Unare in which salinities of $95^{\circ}/_{oo}$ have been recorded after only four months of drying (Okuda et al 1965), there is clear evidence of nutrient concentration by reduction of the total water volume and conservation of the total nutrient content. In the case of a lagoon having anti-estuarine circulation the situation is a little more complex since it could be supposed that the subsurface outflow should carry particulate matter out to sea. This is not generally observed (Postma 1969) and furthermore, a study of phosphorus by Nichols (1966) revealed that the total concentration of this element (largely in the form of suspended particulate matter) increased with distance inwards from the lagoon mouth.

An increasingly important source of nutrient materials in the lagoon environment is from domestic, agricultural or industrial waste. For example, eutrophication was observed by Copeland and Wohlschlag (1968) from industrial and domestic contamination of the coastal lagoons of Texas (U.S.A). The most generally observed source of introduced nutrients however, is that arising from sewage discharges and agricultural run-off (Barlow et al 1963). Even a minor source such as that from power-plant cooling water (Bader and Roessler 1972) can have a considerable local effect.

The general biological effect of large additional sources of nutrient material in a lagoon is a lowering of species diversity within the lagoon, together with an increase in species population (Copeland and Wohlschlag 1968). This has the secondary effect of reducing available oxygen in the lagoon - a factor very important in determining its ability to support a reasonable fish population.

The introduction of toxic pollutants is a further product of intense human activity. Particularly high accumulation rates have been observed in estuarine invertebrates (for example a concentration factor of 70,000 is typical for D.D.T., Butler 1966) and there is need for further research to understand the complex interrelations in the estuarine and lagoon environments (Livingstone 1976).

1.4.2 Processes within the lagoon environment

The fate of dissolved and particulate nutrient material is largely dependant on the hydrography and morphology of the lagoon into which it is discharged. In the open ocean, the flux of nutrients is generally controlled by uptake or assimulation by living organisms, balanced by a supply from regeneration, within and below the photic zone, and combined with a vertical advection of nutrients into it (Pytkowicz 1975). This illustrates that the rate of incorporation of nutrient material is strongly affected by the rate of vertical advection which may thus become a controlling factor in primary production. In the simplest case of an enclosed and vertically mixed shallow coastal lagoon where there are no river inputs nor losses to the sea, it should follow that the overall rate of photosynthetic production depends directly on the rate of regeneration of the limiting nutrient.

This general picture may be modified in various ways :-

(i) By continental supply of nutrients,
(ii) By loss to the sea (flushing and direct outflow) or to the sediments.
(iii) By inhomogeneous systems.
(iv) By other production limiting factors (light, temperature, etc).

By considering existing studies of the processes of regeneration and production in different lagoon environments, it should be possible to see how these factors contribute to the overall chemistry of lagoons.

(a) Regeneration and mobilisation

In a coastal lagoon there are two important sites for the regeneration of nutrients, the water column and the sediments. Whereas in the sea almost all nutrient regeneration takes place in the water column and material reaching the sediment is generally lost (Ryther and Dunstan 1971), in a coastal lagoon the entire process may be contained within a few metres, the boundaries at the air/sea interface and a few centimetres into the sediments.

Various authors have attempted to study the movement of dissolved materials across the sediment/water interface. Experiments using enclosed bottom chambers (Bruce and Hood 1951, Hale 1975) showed considerable movements of dissolved inorganic nutrients. Generally speaking, a large flux of ammonia out of the sediments was observed in all cases; in the case of nitrate and phosphate, a flux in both directions was found, all fluxes being strongly temperature related. Similar studies using small quantities of radioactive tracers $^{32}PO_4$ (Bruce and Hood 1959, Pomeroy et al 1965), ^{60}Co, ^{59}Fe, ^{54}Mn and ^{65}Zn (Parker _et al_ 1963), showed that initial loss of added tracers exhibited a half time of only a few hours, finally reaching an equilibrium between the sediment and water column reservoirs of these materials. These observations support the idea of Pomeroy _et al_ (1965) that the sediment-water exchange of dissolved phosphate may act in a buffering equilibrium to control its concentration in the water.

As yet there have been few complete studies of the size and distribution of elemental reservoirs in coastal lagoons. Parker _et al_ (1963) presented some figures for Zn, Co, Fe, and Mn in a Texas lagoon and found these elements considerably concentrated in sediments and sea grasses with respect to their dissolved concentrations. Perhaps more important than the sizes of these reservoirs are the kinetics of their exchange. Regeneration of dissolved nutrients from the sediments can be controlled by biological, chemical and physical factors.

Biological control may be by bacterial action (Hayes 1964), the total population of bacteria often depending on the texture of the sediments (coarser sediments providing bigger spaces for the development of large populations) (Oppenheimer 1960). Where the substrate is oxygenated, the overall reaction for regeneration is approximately :

$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 138O_2 = 106O_2 + 122H_2O + 16HNO_3 + H_3PO_4$$

(Richards 1965). In the absence of oxygen, bacterial oxidation of any thermodynamically convenient energy source will take place. The denitrification reaction, (Richards 1965) provides a good example :-

$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 84.8HNO_3 = 106CO_2 + 42.4N_2 + 148.4H_2O$$
$$+ 16NH_3 + H_3PO_4$$

A rather more common energy source in the bottom water of stagnant, stratified lagoons and in estuarine and lagoon sediments in general is from the reduction of sulphates to hydrogen sulphide, a process which considerably changes the redox system of the substrate (Hayes 1964, Oppenheimer 1960).

The importance of biological control of regeneration is particularly well established for the phosphate cycle. In a simple adsorption - desorption experiment on estuarine sediments, Pomeroy et al (1965) showed that treatment of the sediments with formalin considerably reduced their capacity for phosphate exchange. For the nitrogen cycle, Okuda (1960) suggested that bacteria probably control ammonia release from sediments, an effect particularly pronounced where sewage outfalls provide large amounts of organic detritus, (Nedwell 1975). However, bacteria are not the only organisms mediating the exchange of dissolved nutrients. Reworking of sediments by marine animals (Hayes 1964) can be an important factor in sediment mixing and detrital breakdown. A particularly thorough study by Kuenzler (1961) of mussel beds (a typical feature of coastal lagoons) showed that these populations of filter feeders are capable of turning over all the particulate phosphorus in a water column in less than 3 days, regenerating around 5% of the material as phosphate and depositing the remaining part as faecal or cell tissue forms This organic phosphorus may then be subjected to regeneration by bacterial attack or may enter the food chain.

Chemical processes are probably the least understood mechanisms of exchange and regeneration. For the case of phosphorus exchange, Pomeroy et al (1965) talk of "sorption" but the formation of inorganic salts such as iron and copper phosphates (Hesse 1962) and their equilibrium control by pH and redox potential (Hayes 1964) cannot be ignored.

Control of nutrient regeneration by physical factors is generally of two types, kinetic control (by temperature) and dynamic control (water movements). In laboratory experiments on ammonia release from sediments, Okuda (1960) found that the amount of ammonia released increases in direct proportion with the temperature (within his experimental range of 5°C to 30°C). This observation, which probably relates to temperature effects on bacterial activity, is particularly important when comparing tropical and temperate lagoon chemistry. Additionally, water movements may considerably affect nutrient regeneration. Resuspension of sediments by turbulence may cause a local increase in dissolved phosphate concentrations (Nichols 1966). Tidal exposure and partial drying of the surface layers of mudbanks, followed by re-immersion, probably accelerates the regeneration of nutrients (Oppenheimer and Ward 1963).

The final comment regarding nutrient regeneration is with respect to its importance in lagoon eutrophication, Ryther and Dunstan (1971) present considerable evidence to suggest that the regeneration of phosphorus is generally more rapid than that of ammonia. In a marine system, where nitrogen fixation is generally thought to be limited and where nutrient limitation is observed, the limiting nutrient will almost always be nitrogen provided that its principal source is from the decomposition of organic matter.

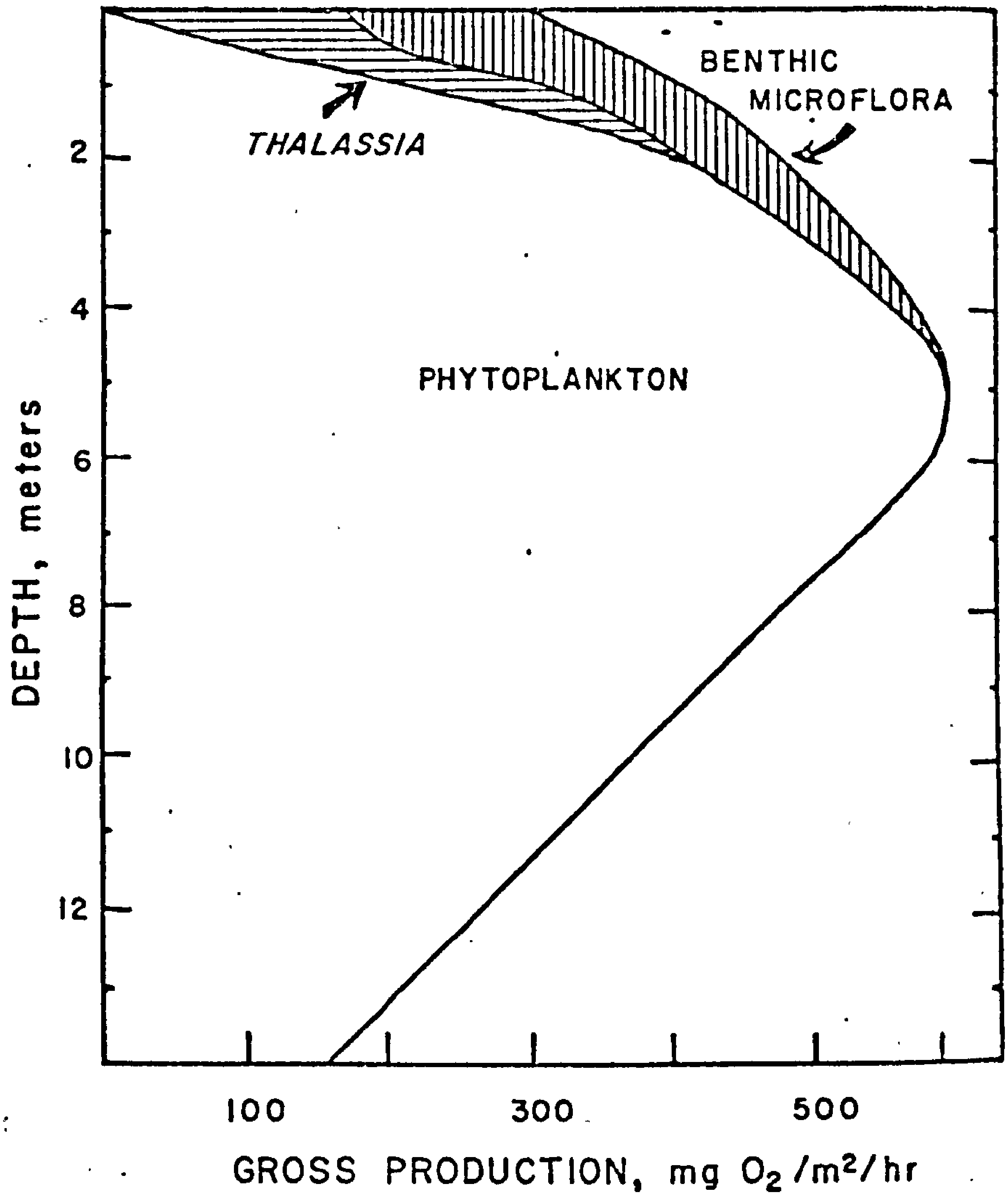
(b) Primary Production

Primary production is of great chemical importance in the lagoon environment as it is the only means for fixation of carbon entering the food chain and the principal pathway by which inorganic nutrients and carbon are converted to cell tissue.

Primary production may be promoted by a direct input of nutrients into the lagoon or by regeneration of inorganic nitrogen or phosphorus. This is particularly well illustrated in figure 1.1 from Pomeroy (1960). The figure illustrates variation of gross primary productivity for stations of

Figure 1.1

VARIATION WITH DEPTH OF THE RELATIVE PRIMARY PRODUCTION OF THE PLANT POPULATIONS IN BOCA CIEGA BAY (POMEROY 1960)


BENTHIC MICROFLORA
THALASSIA
PHYTOPLANKTON
DEPTH, meters
2
4
6
8
10
12
100
300
500
GROSS PRODUCTION, mg O_2 /m^2/hr

different water column depth in Boca Ciega Bay, a large shallow lagoon. Optimum productivity was observed in waters of 5-7 metres depth after which there was a gradual fall-off. This effect illustrates how a high productivity is favoured by shallow conditions, conditions in which rapid turnover is most easily facilitated.

Effects limiting primary production in a lagoon may be kinetic (the rate of regeneration of a limiting nutrient and its transport) or physical. The latter case includes limitation by lowered temperatures or by reduced light penetration. Light attenuation, particularly in very shallow lagoons where windy conditions easily re-suspend sediments, has been shown to restrict primary productivity, in one case to lower values than in the adjacent sea (Nichols 1966).

Measurement of primary productivity has generally been made by following oxygen changes, either in-situ or in light and dark bottles and bell-jars. A detailed presentation of these methods is given by Odum (1960), Odum and Wilson (1962) and Odum et al (1963).

Primary fixation of nitrogen does not appear to have been studied in the lagoon environment. In the very similar conditions found in the Waccasassa, a shallow embayment in the west coast of Florida (U.S.A), Brooks et al (1971) measured up to 6 nanograms N/g- sediment-hour fixed by bacteria within the first 2-5 cm of sediments. The results are of a similar magnitude to those presented by Herbert (1975) for the much colder Clyde estuary in Scotland and suggest that similar observations might be expected in many coastal lagoons.

(c) Primary production by specialised tropical communities

Of the primary producing plants in tropical coastal lagoons, three large groups, not generally found in open ocean ecosystems, may account for a large proportion of the total primary production in the system. Their presence may often completely alter the chemistry of a lagoon. These are marine grasses, algal mats and mangrove forests.

Beds of underwater marine grasses are a common feature in shallow clear waters, both in tropical and temperate regions. Temperate beds however, are subjected to strong seasonal changes and rarely exhibit the closed community structure that develops in the tropics (Odum 1974). Productivity of these grasses is generally very high (Wood et al 1969) and may be strongly influenced by the rate at which water currents present dissolved substances to the growing plants (Conover 1968). Many of the plants may be covered with epiphytes which can account for 25 to 33% of the total community metabolism (Jones 1968).

The importance of marine grasses is in their role of producing detrital material. Few secondary organisms graze these plants and as many as 2% of the leaves of the plants may fall each day (Wood et al 1969). These leaves are rapidly decomposed by bacteria, the detritus entering the food chain through consumption by benthic animals and these in turn, may be consumed by larger animals including fishes (Odum 1974). Regeneration of nutrients from plant detritus, even through sulphate reducing bacteria (Wood et al 1969), probably provides the main source of nutrient material for marine grasses. An additional nutrient source results from the trapping of nutrient

0.5V. The mats are responsible for fixing large amounts of carbon whilst permitting an internal, upward transport of anaerobically regenerated nutrients in order to maintain photosynthesis. Inorganic carbon may also be precipitated in this process (in the form of grains of aragonite) probably as a result of action by ammonifying bacteria (Dalrymple 1965). Chemical information regarding these mats is very limited and many further studies are required.

Unlike the two previous examples, mangroves have a wide tolerance of salinity conditions, growing in shallow water along most of the coastal margins and along the banks of estuaries and lagoons between latitudes 25° S and 25°N (Kuenzler 1974). Their ecology has been the focus of a considerable amount of research and is dealt with in an excellent review by Lugo and Snedaker (1974) and also by Kuenzler (1974). Their principal function is to fix coastal margins, establishing, by gradual species succession, marshes and finally tropical forests. In coastal lagoons, their role is also to provide a major source of detritus (from leaf and twig fall) and thus are of direct importance in maintaining oyster, shrimp and fish stocks. The chemistry of mangrove systems is a relatively simple open cycle in which particulate nutrients transported through the mangrove roots by tidal or river flow movements are incorporated into the sediments by the associated benthic organisms (or by chemical and biochemical uptake), from where they may be taken up by the mangroves. Net primary productivity of between 1.3 and 7.5 gC/m^2 day has been reported for mangrove communities (Lugo and Snedaker 1974), part of which is carried into the water by falling leaves and twigs. River flow and current movements tend to disperse the detrital material produced, and its gradual subsequent decomposition leads to the regeneration of nutrients. For a large mangrove swamp in Florida (U.S.A), Heald (1971) calculated that over half the annual production of mangrove debris is exported to adjacent lagoons. The onset of the rainy season in a tropical area may produce chemical consequences in a lagoon by introducing much of the organic detritus in a short time period. This considerably increases the bacterial population and the oxygen demand and thus reduces the available dissolved oxygen.

Considering the various processes that take place within a lagoon, it may be commented that the manner in which a nutrient cycle may have developed in any particular lagoon, depends entirely on its particular physical conditions, conditions determining the degree to which each of the processes outlined will act. The infinite number of combinations of these conditions makes it difficult to form generalisations concerning chemical cycles in lagoons. Lagoons are generally nitrogen limited, nitrogen reservoirs being located in sediments and plants (see above) and additionally in the form of dissolved organic nitrogen (Okuda et al 1965, Bonilla and Benitez 1972). Considerable interchange between the sediments and water column is observed, mediated by biological and chemical effects. Lagoons having high primary production generally possess ecologically important detrital cycles.

1.4.3 Processes involving loss of substances from the lagoon

Dissolved and suspended substances may be lost from a lagoon by flushing into the sea or by permanent incorporation into the sediments. Nutrient losses are clearly related to the flushing time of the system. Sedimentary losses occur from the production of non-regenerable minerals or sometimes as the result of sudden heavy sedimentation trapping former surface sediments, for example during a hurricane (Scott et al 1969). Various authors (e.g. Birke 1974, Scott et al 1969) have discussed the possibility that the sedimentary processes in lagoons might have been one of the factors responsible for the production of present hydrocarbon deposits.

The various means of loss from a lagoon maintain an overall equilibrium in the system. Any sudden change in the input of dissolved substances into the lagoon will thus have effects within it, causing eutrophication or impoverishment. A good example of impoverishment is given by Lugo and Snedaker (1974) where reduction of nutrient inputs into a mangrove system from change of land use, resulted in destruction of mangrove communities within a period of 10 years.

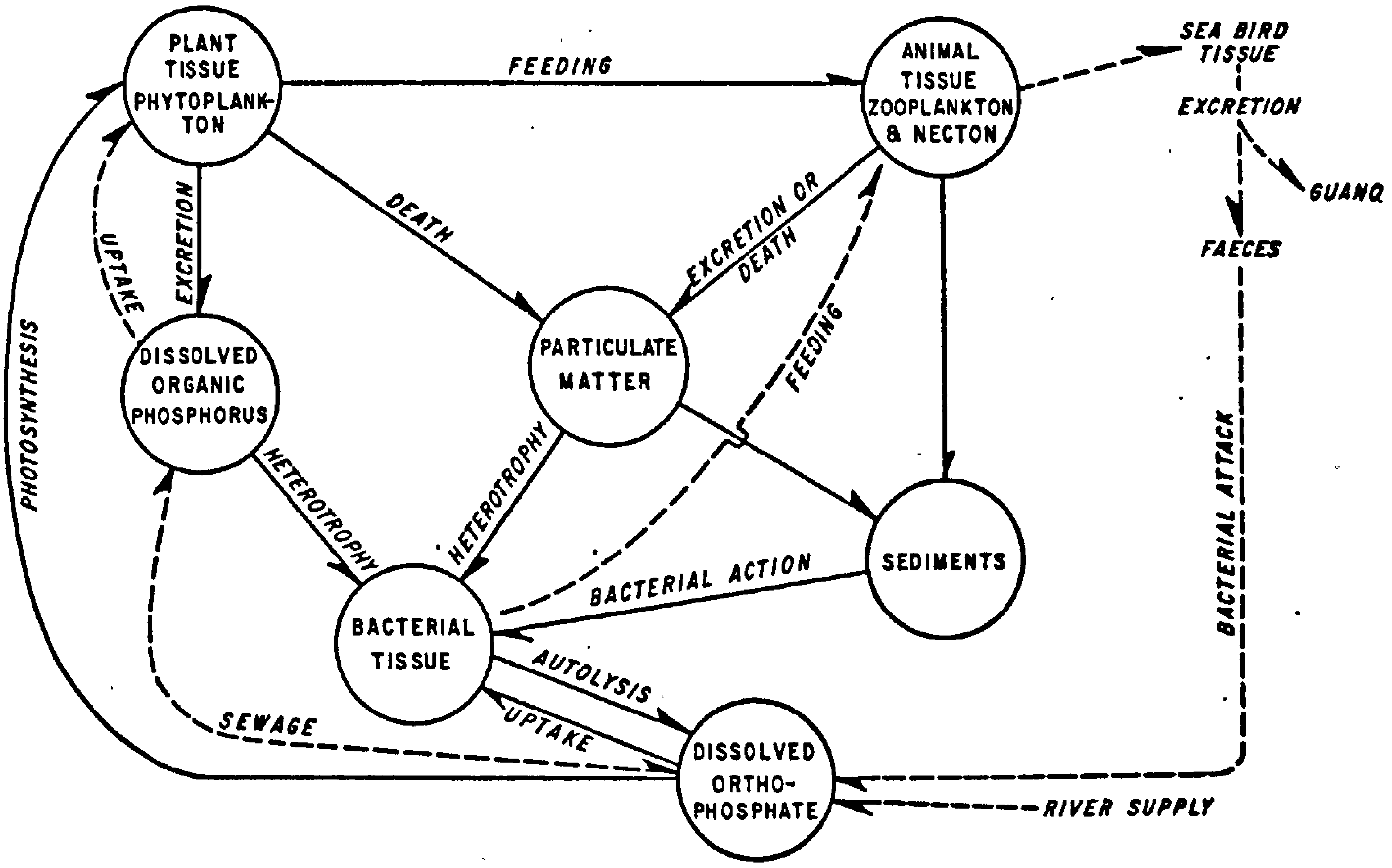
1.4.4 Summary

The description of chemical and biochemical processes given above gives a general impression of some of the most important features of the lagoon environment. Sufficient information is not yet available to construct even skeleton mineral cycles for the common elements. In the case of phosphorus however, it is possible to show the lagoon cycle in schematic form. In figure 1.2

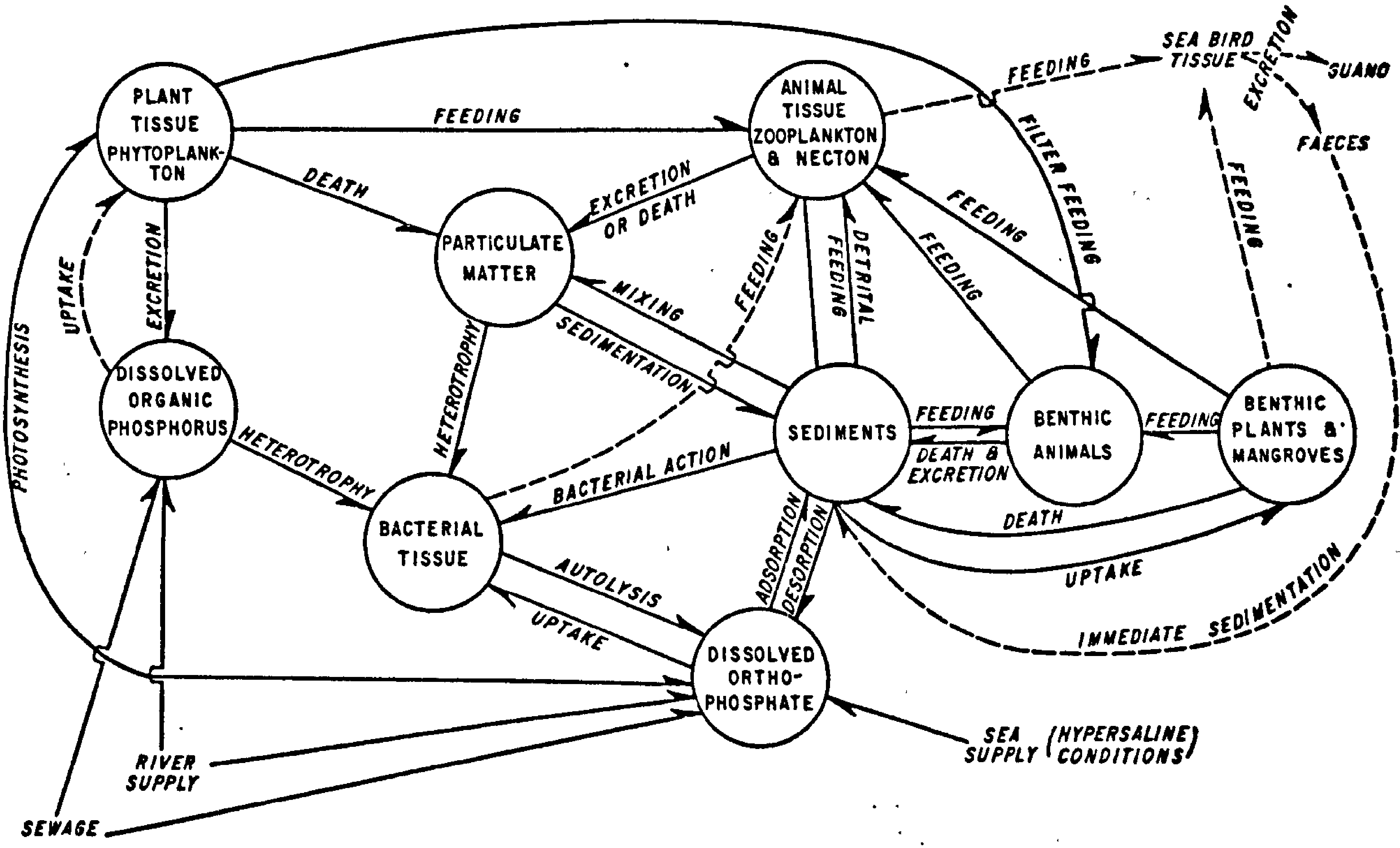
Figure 1.2

PHOSPHORUS CYCLES IN THE OPEN SEA AND SHALLOW LAGOONS

OPEN SEA



SHALLOW COASTAL LAGOON



PHOSPHORUS CYCLES IN THE OPEN SEA AND SHALLOW LAGOONS the phosphorus cycle for the sea is compared with the lagoon cycle. Processes shown for the open sea are described and referenced in Riley and Chester (1971) and additional processes shown for lagoons have been described and referenced earlier in this section. On the present diagram, continuous lines indicate major pathways and dashed lines minor ones. Ringed names are reservoirs within the environment concerned and other names are external reservoirs.

It can be seen from fig. 1.2 that the overall phosphorus cycle in coastal lagoons shows more pathways than that for the open sea since it involves interactions with benthic and sedimentary processes. External inputs become more important and there is the possibility of sewage constituting a major phosphorus source, since the discharge is into a smaller volume of water. Interchange of sediments and particulate matter is shown (resuspension) and this factor makes chemical measurements of individual components of the cycle extremely difficult.

The phosphorus cycle as shown is quite useful but lacks quantitative information. This is often very difficult to obtain, requiring complicated tracer experiments, results generally only being valid for one particular environment. The study of the kinetics of such a system provides one of the most interesting challenges for the marine chemist.

1.5 The biology of lagoons

A general review of biological processes in coastal lagoons is really beyond the scope of the present study and general discussion of primary production has been included in the previous section. However, it is worthwhile making a few general comments.

Many of the secondary producers in coastal lagoons have at least part of their life cycle outside the lagoon (e.g. Penaeid shrimps, Mullet, Swimming crabs) and are thus probably very sensitive to hydrological changes. Of these species, detrital feeders are commercially very important. Hellier (1962) found some relation between primary production and fish production with a fish production efficiency (fish production/primary production) of 0.074%, but the results are not conclusive. Many lagoons, depending on their physical, chemical and sedimentary conditions, also support large populations of filter feeding mussels and oysters. Useful reviews include that of general estuarine ecology by Odum (1971); of lagoon ecology by Hedgpeth (1957), concerning potential production by Vanucci (1969) and regarding phytoplankton by Margalef (1969).

2. THE SURVEY AREA

According to Lankford (1977), there are some 125 coastal lagoons along the 6,200 miles of Mexican coastline. These exemplify a large variety of lagoon types, both physically and geologically.

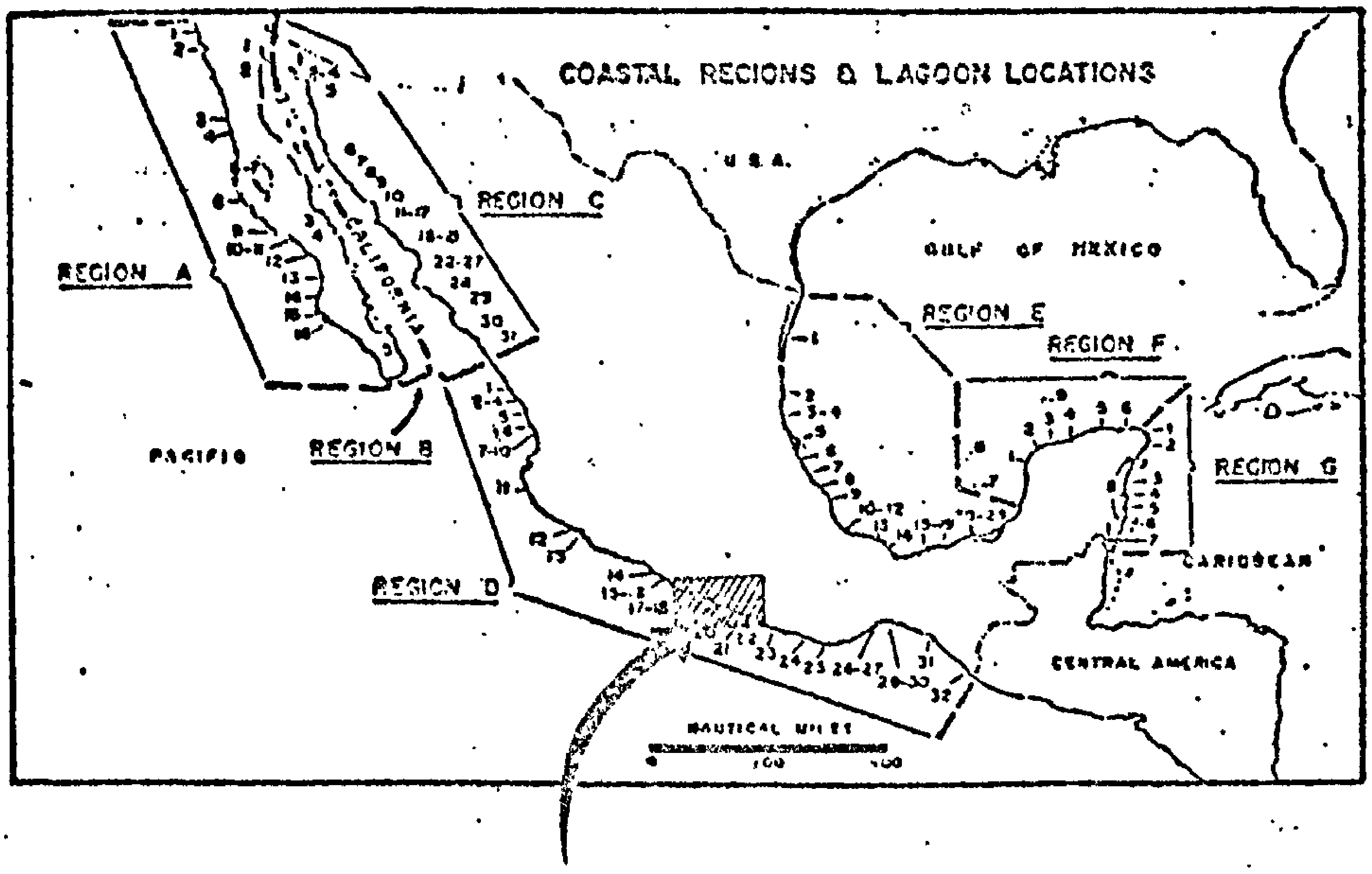
Geological classification of all the Mexican lagoons is considered by Lankford (1977), a review which represents the only coherent study of the area. He presents five basic types of coastal lagoon, classified according to their mode of formation as :-

I Differential Erosion
II Differential Terrigenous Sedimentation
III Barred Inner Shelf
IV Organic
V Tectonic - Volcanic

Many of these basic types have further sub-divisions according to their detailed geological structure. Having presented this classification scheme, he divides the Mexican coasts into seven convenient regions (based on the geographical distribution, geological, climatological and oceanographic features - see fig. 2.1) and examines the classification of lagoons within them. About half of the lagoons fall into the "type III" classification, a type particularly common in the Pacific Mainland coast (Region D) Type II lagoons predominate along the Gulf of California, mainland coast (Region C) and that of the Gulf of Mexico (Region E). General distribution is as follows : type I, 22 lagoons; type II, 30 lagoons; type III, 60 lagoons; type IV, 6 lagoons and type V, 5 lagoons.

Figure 2.1

COASTAL REGIONS OF MEXICO (after LANKFORD 1977)

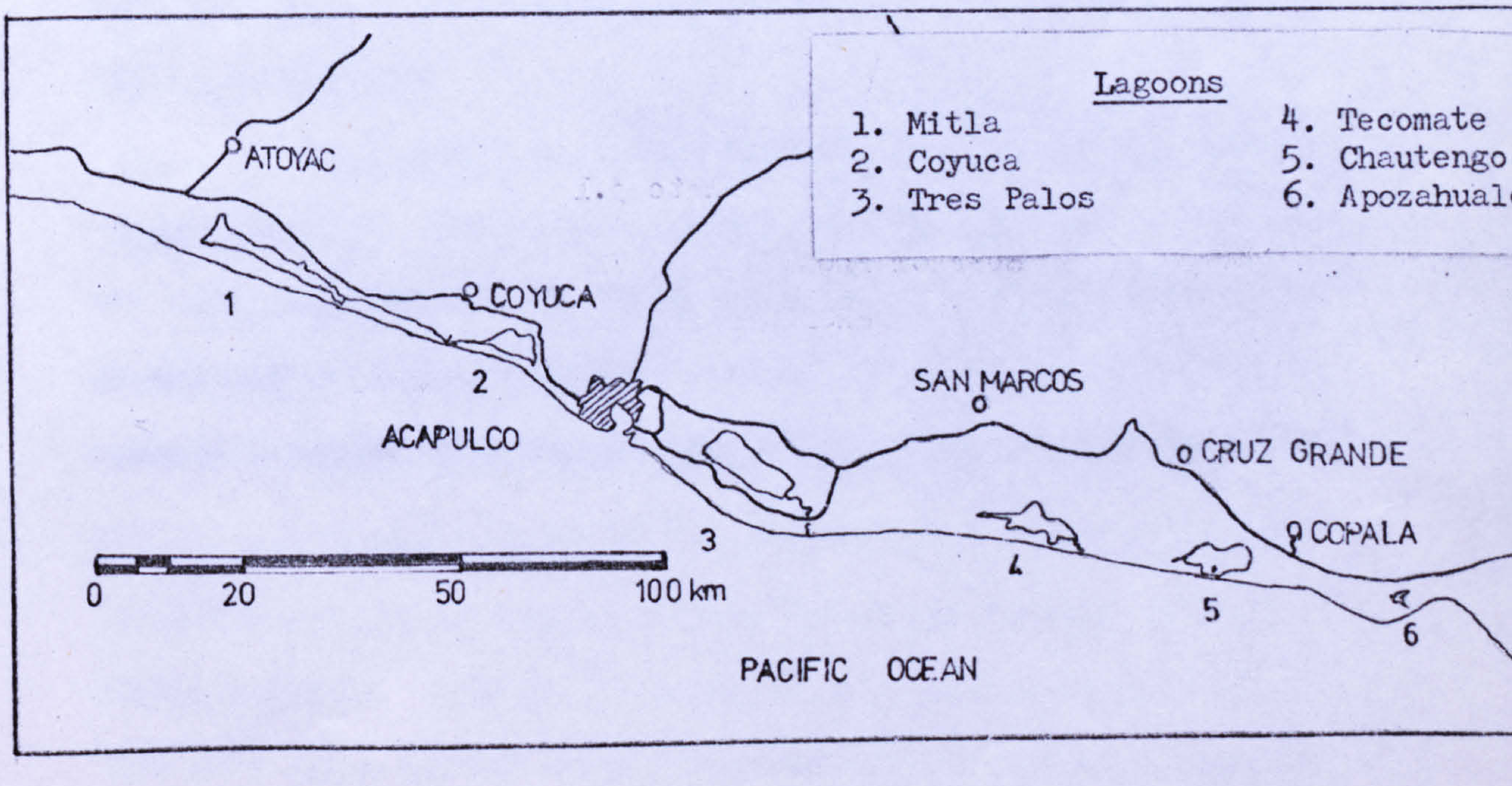

COASTAL REGIONS & LAGOON LOCATIONS
U.S.A.
GULF OF MEXICO
REGION A
REGION B
REGION C
REGION D
REGION E
REGION F
REGION G
CALIFORNIA
PACIFIC
CARIBBEAN
CENTRAL AMERICA
NAUTICAL MILES
100
400

See plate 2.1

Plate 2.1

TOURIST MAP OF THE GUERRERO COAST.


Coyuca de Benitez
Xaltianguis
Tierra Colorada
Xalpatlahuac
ACAPULCO
A MEXICO
ACAPULCO DE JUAREZ
Cruz Grande
O C E A N O P
ESCALA GRAFICA


Lagoons
1. Mitla
2. Coyuca
3. Tres Palos
4. Tecomate
5. Chautengo
6. Apozahual
ATOYAC
COYUCA
ACAPULCO
SAN MARCOS
CRUZ GRANDE
COPALA
1
2
3
4
5
6
0
20
50
100 km
PACIFIC OCEAN

Unfortunately, no thorough examination of the physical, chemical or biological characteristics has been made to compare with the geological observations. Physical characteristics tend to follow climatic conditions and coastlines towards the north of Mexico generally experience much more arid conditions than those of the south and east (Tamayo 1962). Thus, most of the published studies of northern lagoons show them to have anti-estuarine circulation (e.g. in Region A, Phleger and Ewing 1962, Postma 1965; in Region C, Nichols 1966), or to form evaporating basins as in the case of the Laguna Madre of Tamaulipas (Copeland 1967). Further south, rainfall is seasonal and occurs almost exclusively in the summer months (Tamayo 1962). Most of the larger Mexican rivers drain towards the Gulf of Mexico. Rivers draining towards the Pacific often have a very limited and seasonal flow with the exception of the Rio Balsas which is one of the major rivers of Mexico. Lagoons in the southern Gulf of Mexico are thus generally not hypersaline and are commonly mesohaline. Those of the Pacific coast show a wide range of conditions, including large seasonal variations, conditions which largely depend on the drainage pattern and local rainfall.

The research area selected was the coast of the State of Gurrero, Mexico. The choice of this area was based on two factors: (1) The relative ease of access of the coast from the laboratories in the City of Mexico (maximum 10 hours drive) and (2) The great variety of lagoon environments encountered along the same coastline.

2.1 Description

2.1.1 Topography

The coast of Guerrero (see plate 2.1) consists of a 300 mile long narrow, sandy coastal plain, broken occasionally by granite outcrops and abruptly yielding on its landward side to the rocky hills and mountains of the Sierra Madre del Sur. The coastal plain falls naturally into two regions of approximately equal length (1) the Costa Grande, which stretches from the wide alluvial delta of the Rio Balsas (to the North-west) to the rocky bay of Acapulco (to the south-east) and (2) the Costa Chica which continues south-east into the state of Oaxaca. The Costa Grande is generally narrow (0-10 miles wide) and more undulating than the Costa Chica (14-20 miles wide). Both areas are covered with vegetation during at least part of the year.

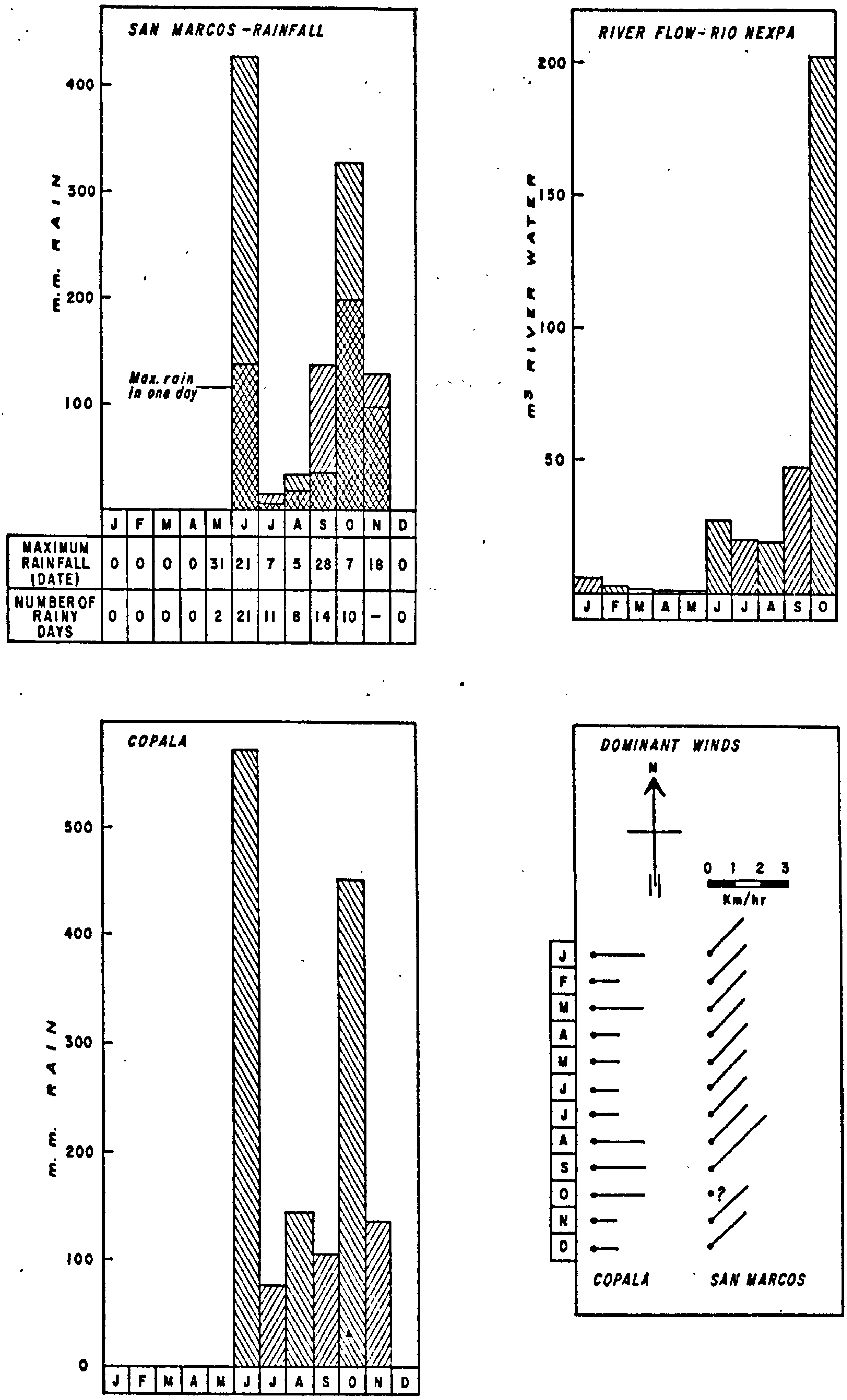
The Guerrero sea coast is an almost continuous low sandy beach, broken only where outcrops of the Sierra reach to the sea. Various small rivers cross the coastal plain from where they seasonally discharge into the sea or into the numerous small coastal lagoons. These lagoons, with their associated drainage canals, occupy almost half the length of the coast, their width never exceeding 5 km.

2.1.2 Climate

The Guerrero coast experiences a tropical climate. The average temperature is 26°C (Recursos Hidraulicos 1975) with an annual range of 3 deg. C. between the summer maximum and the winter maximum. Maximum temperatures in summer may rise to more than 40°C and a diurnal range of around 10°C is generally observed.

Figure 2.1

GENERAL CLIMATOLOGICAL CONDITIONS AFFECTING THE LAGUNA CHAUTENGO AREA



	J	F	M	A	M	J	J	A	S	O	N	D
MAXIMUM RAINFALL (DATE)	0	0	0	0	31	21	7	5	28	7	18	0
NUMBER OF RAINY DAYS	0	0	0	0	2	21	11	8	14	10	–	0

GENERAL CLIMATOLOGICAL CONDITIONS AFFECTING THE LAGUNA CHAUTENGO AREA

2.1.3 River discharges

River flows in the many small rivers draining the coastal plain, largely reflect the local seasonal rainfall and many of the rivers become completely dry in the dry season. Data for a typical example, the Rio Nexpa of the Costa Chica, is shown on fig. 2.2 (compiled from data loaned by the Secretaria de Recursos Hidraulicos). The limited response to the initial period of heavy rainfall (June) is probably a result of 'soaking' in the drainage basin (i.e. the water which is required to give initial soil saturation).

The large annual variation in total rainfall is also reflected by large variations in total annual discharge of the rivers. This is illustrated for the Rio Nexpa in Table 2.1 (data from the Secretaria de Recursos Hidraulicos).

Table 2.1 - Total annual discharge of the Rio Nexpa

Year	Discharge millions of cubic metres
1969	1192.6
1970	970.6
1971	307.9
1972	252.0
1973	611.3
1974	1045.5

The effect of cyclones on these rivers may also be very marked. In the case of the Rio Nexpa, heavy rains from a small cyclone in October 1976 increased the flow rate of the river from $36m^3$/sec to $648m^3$/sec in two days. Previous cyclones had considerably changed the course of this river, diverting its discharge from one lagoon to another.

2.1.4 Coastal Oceanography

Oceanographic observations along the coast of Guerrero have been limited to tidal observations and predictions for the port of Acapulco and a general consideration of wave regimes (Lankford 1977).

The average tidal range for Acapulco is about 0.5 metres and reaches 0.65 metres in spring tides (Institute de Geofisica 1976). The form of the semidiurnal tidal wave is such that the lowest low water is followed by the highest high water, an effect which would be expected to produce a current velocity maximum on the flood tide in any lagoon inlet which is not dominated by river run-off (Lankford 1977).

The wave regime on the Guerrero coast is, except in the case of tropical cyclones and hurricanes, generally dominated by the Pacific Ocean swell. The direction of this swell is seasonal, a northern hemisphere swell dominating from October through March and a southern hemisphere swell dominating from April through September. This change may have important consequences on the longshore drift of sediments along the coast.

Table 2.2 - General characteristics of coastal lagoons in Guerrero

Lagoon	Area (km^2)	Type of Run-off Received	Type of Sea Connection	Typical Annual Salinity Range $^o/_{oo}$	Source of Information
Costa Grande					
Potosi	ca 6	Seasonal River overflow	Seasonal	15-40	(2) (4)
Cuajo	2	Direct run-off only	Brief connection in High rainfall years	15-200	(3) (4)
Nuxco	8	Small seasonal river	Seasonal	15-23	(1) (3) (4)
Mitla	36	Direct run-off only	Infrequent, in hurricanes	2-4	(1) (3) (4)
Coyuca	29.5	Indirect river supply	Long channel to seasonal inlet	1-3	(3)
Costa Chica					
Tres Palos	60	Small seasonal river	Long channel to seasonal inlet	2-4	(3) (4)
Tecomate	25	Direct run-off only	Long channel to ephemeral (2) inlet	9-21 closed year 8-55 normal year	(1) (4)
Chautengo	36	Two seasonal rivers	Seasonal	5-30	(1) (4)
Apozahualco	2	Direct run-off only	Seasonal	14-180	(2) (4)

Notes - 1 The expression 'Direct Run-off' refers to precipitation into the Lagoon and run-off from its immediate drainage basin.

2 An 'Ephemeral Inlet' does not open every year.

Information sources (1) Mandelli & Botello (1976) (2) Castellanos (1975) (3) Recursos Hidraulicos (1975)

(4) Personal Observations.

more probably a result of the high lagoon water level (following prolonged run-off) increasing the hydrostatic pressure on the bar and saturating the bar sands with lagoon water. This effect lowers the resistance of the normally compacted bar sands to wave erosion and the bar breaks open as a result of internal hydrostatic pressure and external erosion.

A great variety of salinity conditions are found in these lagoons. Using the depth data together with the information in Table 2.2, it is possible to propose a general grouping of these lagoons :- Group (1) lagoons are shallow and with no direct river inputs. Following bar closure and the start of the dry season, the volume of these lagoons is rapidly reduced by the high evaporation rate observed along the entire coast. Thus hypersaline conditions are observed in winter and spring, before the summer rains refill these lagoons with water. Examples of this lagoon type are Cuajo, Apozahualco and in certain years Tecomate. Group (2) lagoons are slightly deeper than those of Group (1), have seasonal river inputs and a direct seasonal inlet to the sea. The presence of river inputs maintains a nett outward flow of water across the bar during the rainy season and following bar closure, helps to counteract the effects of evaporation from the lagoon during the dry season (until the river eventually dries up). The greater depth of these lagoons than those of Group (1) also means that a similar rate of evaporation will have a smaller effect on salinity. Hence Group (2) lagoons are generally hyposaline, but may become slightly hypersaline in the dry season. Examples of the group are Potosi, Nuxco and Chautengo. Group (3) lagoons are deeper than those of the previous groups, they are isolated and if connected to the sea are connected via long narrow channels and may or may not have river inputs. These lagoons are not generally affected by tidal movements, sea water probably only entering by seepage through the sand bar from the sea or by a saline intrusion along the discharge channel to the sea. They exhibit very low salinity conditions throughout the year with only small salinity variations. Lagoons within this group are Mitla, Coyuca and Tres Palos.

2.2.2 Formation

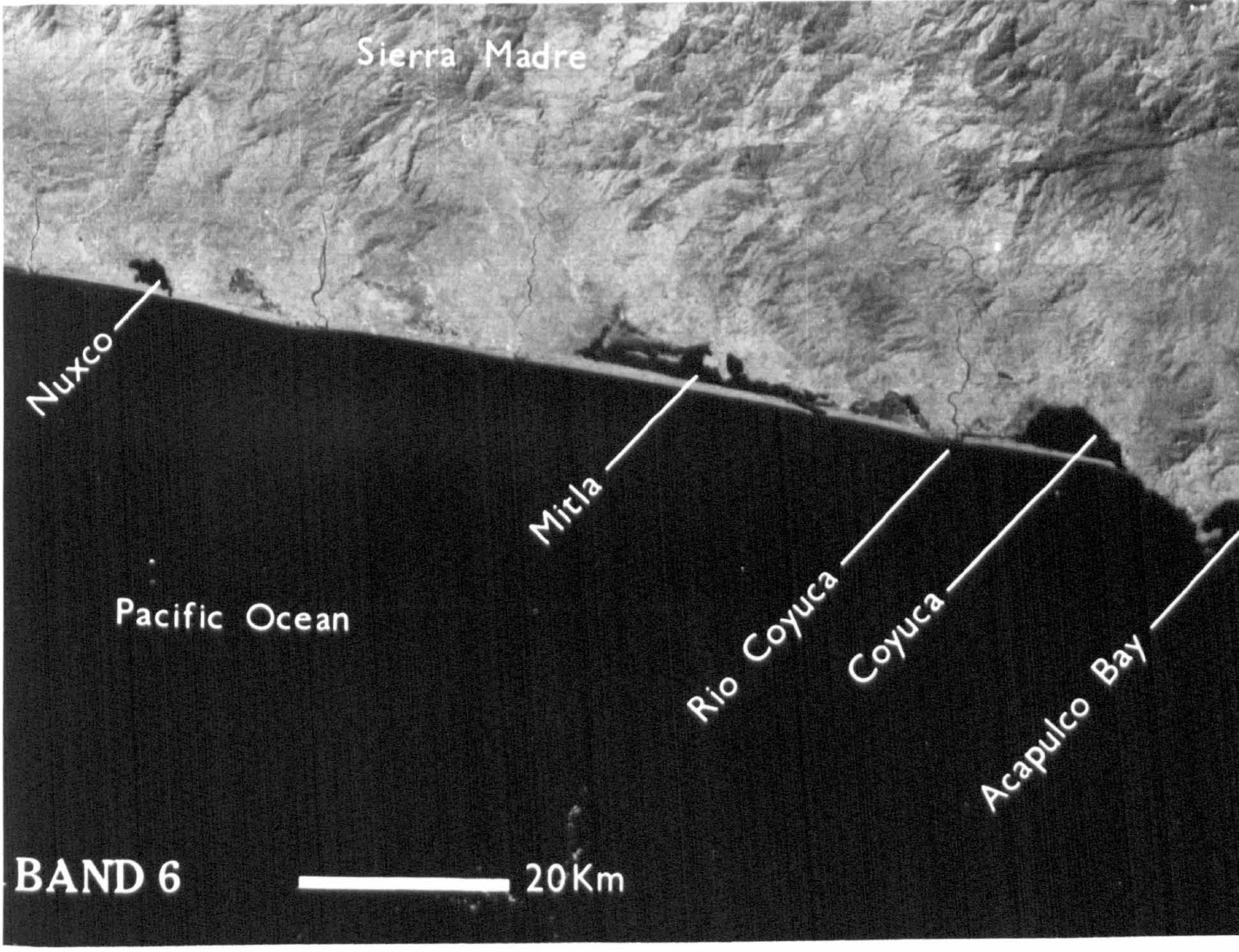
Lankford (1977), using the classification discussed earlier in this chapter describes almost all the lagoons of Guerrero as "Barred inner shelves". The only exception is the tiny lagoon "Salinas de Cuajo" which he describes as formed by "Differential erosion" as a barred drowned valley.

Of the barred inner shelf lagoons in Guerrero, six are described as "Barrier lagoons", the barriers having been formed parallel to the coast (and probably connecting rocky headlands) around 5,000 years ago and as described in Section 1.1. The remaining two lagoons, Potosi and Apozahualco, were formed as "Cuspate lagoons" with sand barriers forming two sides of a triangle, the apex being formed by a nearshore rock outcrop.

The original barred inner shelves of the Guerrero coast were probably long narrow lagoons that have since become divided and isolated by the formation of river deltas. Some of these lagoon segments have now become completely infilled or exist as marshes. This is evident from the satellite photographs shown in plate 2.2 and 2.3 (N.A.S.A. - E.R.T.S. photographs, courtesy of CETENAL Mexico). Plate 2.2 shows part of the Cuerrero coast, north-west of Acapulco. The photographs are taken on two frequency bands,

Plate 2.2

SATELLITE PHOTOGRAPHS OF THE GUERRERO COAST
NORTH-WEST OF ACAPULCO.


Sierra Madre
Nuxco
Mitla
Rio Coyuca
Coyuca
Acapulco Bay
Pacific Ocean
BAND 6
20Km

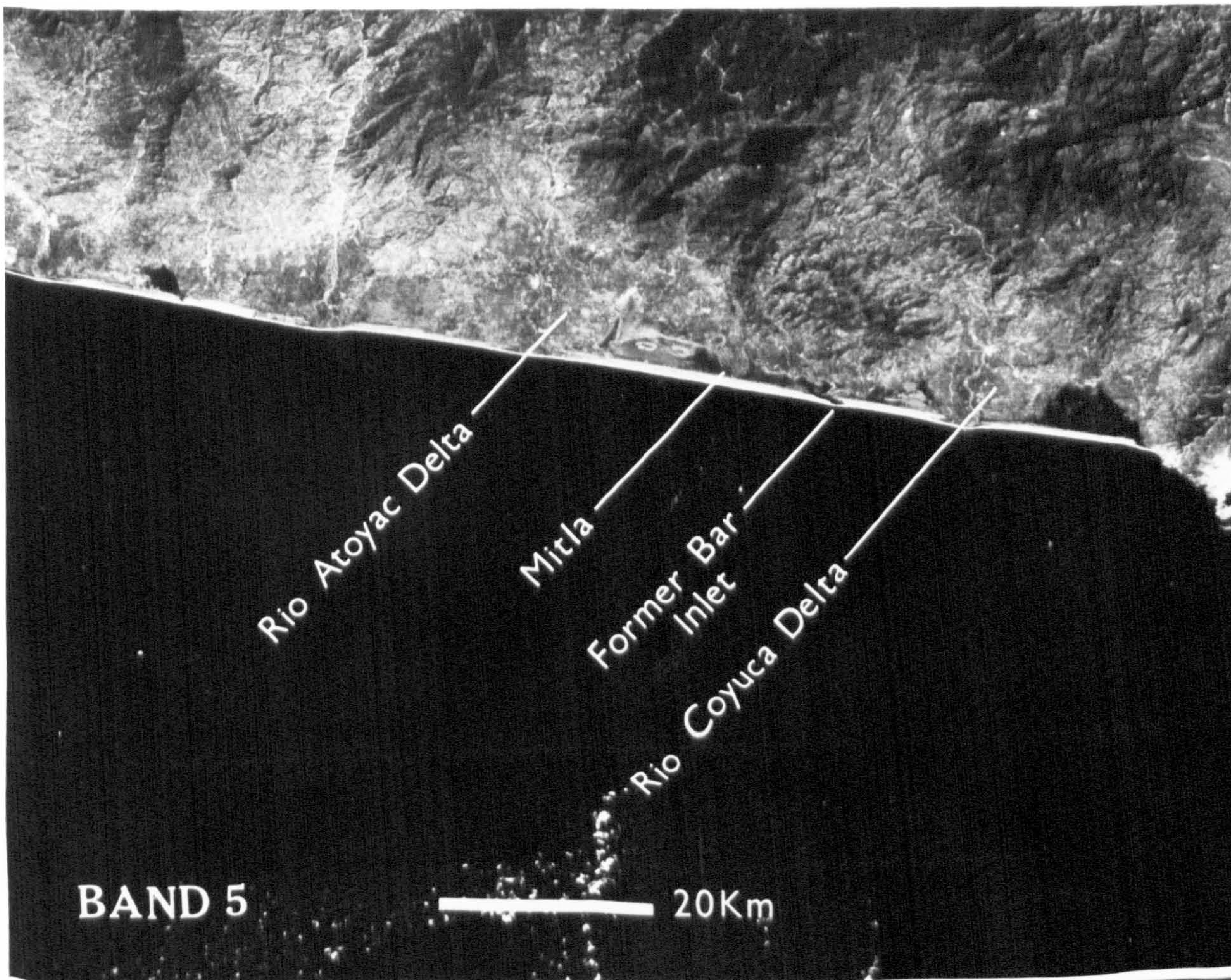
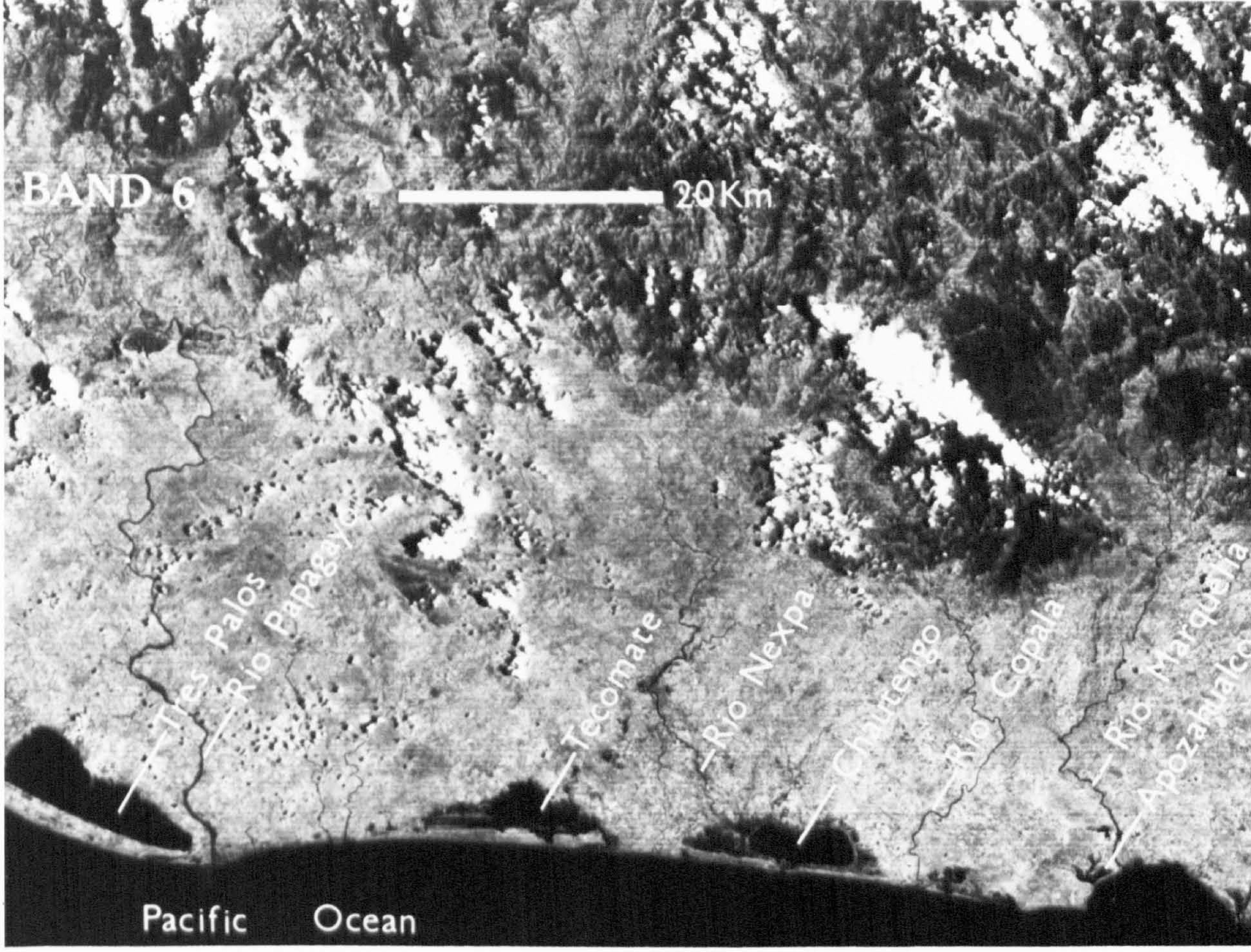
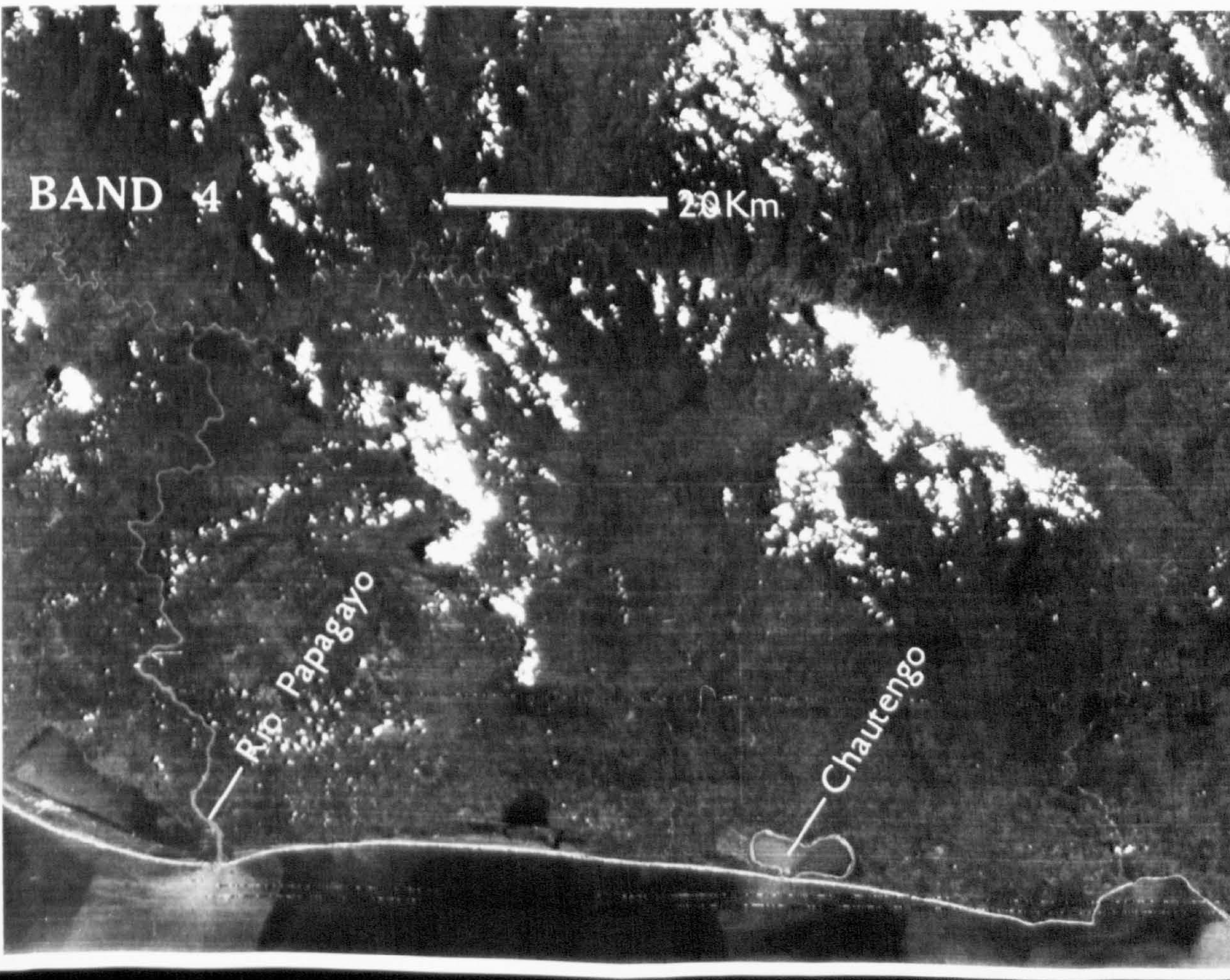

Rio Atoyac Delta
Mitla
Former Bar Inlet
Rio Coyuca Delta
BAND 5
20Km

Plate 2.3

SATELLITE PHOTOGRAPHS OF THE GUERRERO COAST
SOUTH-EAST OF ACAPULCO.


BAND 6
20Km
Tres Palos
Rio Papagayo
Tecomate
Rio Nexpa
Chautengo
Rio Copala
Rio Marquelia
Apozahualco
Pacific Ocean


BAND 4
20Km
Rio Papagayo
Chautengo

the band 6 photograph was taken at a frequency particularly sensitive to vegetation and that at band 5 was at a frequency useful for observing topographical features including river beds and beaches. The main features of each plate are marked. On the band 6 photograph, existing coastal lagoons can be clearly seen as black features and infilled lagoons are seen as grey patches on the coastal plain. The band 5 photograph particularly clearly illustrates the narrowness of the coastal plain and the intrusion of river deltas. Additionally, the photograph highlights the width of the coastal sand barriers. The sand barriers appear as almost breached in the case of the Laguna Mitla and the Laguna Coyuca but both features are former inlets, the present discharge of the Laguna Coyuca and flood discharge of the Laguna Mitla are through narrow channels to the outlet of the Rio Coyuca.

Plate 2.3 shows part of the coast to the south-east of Acapulco. The photographs shown are on bands 6 and 4. Band 4 is at a frequency particularly sensitive to all suspended material in water which appear as whitish patches in the photograph. The band 6 photograph shows the various coastal lagoons together with their associated "marsh" areas (the photograph was taken during the height of the rainy season 1973) and the river courses across the coastal plain. Both the Lagunas Tres Palos and Tecomate discharge into the sea through narrow channels on their easterly extremes. The sea inlet of the Laguna Chautengo is in the central part of its barrier. The band 4 photograph shows particularly clearly the plume of the Rio Papagayo as it discharges into the sea. This river is well known in the rainy season for the manner in which it gives a brown discolouration to the sea in the region of its discharge (e.g. see Tamayo 1962). Perhaps more interesting is the discharge plume off the barrier inlet of the Laguna Chautengo. Areas having large amounts of suspended material appear both within the lagoon and as a plume beyond it. This suggests an active process of transport of particular material from the lagoon and possibly of suspension within it.

The processes of division and isolation of lagoons are strongly reflected in their hydrography, chemistry and productivity. The present study attempts to relate the physical conditions and structure of the lagoons to their chemistry.

2.2.3 Chemical Features

The only reliable chemical data available regarding lagoons in the coast of Guerrero is that of dissolved nutrients, obtained in four seasonal surveys in the Lagunas Nuxco, Mitla, Tecomate and Chautengo during 1975 by Mandelli and Botello (1976). They found that very small concentrations of dissolved nitrates and nitrites were a general feature of these lagoons and that, in many cases, the only inorganic nitrogen nutrient existing in measurable concentrations was ammonia. Reactive and total phosphorus however, were always present in appreciable concentrations, concentrations which were found to be fairly stable throughout the year. These results are very similar to those reported by Okuda _et al_ (1965) in the comparable conditions of the tropical Laguna Unare in Venezuela. However, the studies conducted by Okuda _et al_ (1965) and Bonilla and Benitez (1972) revealed that the largest dissolved reservoirs of nitrogen were in the form of organic nitrogen compounds.

A topic of special interest is the effect of isolation on the chemistry and productivity of tropical coastal lagoons. A study of the Laguna Mitla (Mandelli and Botello 1976), a largely isolated lagoon with no direct river inputs, has shown that it appears to support a very large population of photosynthetic organisms. Furthermore, very large diurnal changes in dissolved oxygen concentrations were observed, suggesting a high rate of photosynthesis and respiration in the lagoon. Similar phenomena have been observed in other isolated tropical lagoons (e.g. Okuda *et al* 1965). In contrast, seasonally opening lagoons appear to support a smaller population of photosynthetic organisms (Mandelli and Botello 1975, Licea *et al* 1976) but a higher species diversity of all organisms is encountered. This implies that such lagoons would also present more favourable conditions for the development of a mixed population of commercially important species (fish, shrimp, shellfish etc).

The rather incomplete information regarding the response of chemical environments to different hydrographic regimes leads to many unresolved problems. For example, how can such an isolated environment as the Laguna Mitla support a large population of phytoplankton ? In the previous chapter it was suggested that the productivity of a lagoon, closed to the sea and without the influence of run-off, should depend directly on the rate of regeneration of the limiting nutrient, which should be nitrogen. If this hypothesis is correct then such lagoons as Mitla could provide the opportunity to test it and to study the chemical processes involved in the entire annual cycle of lagoons receiving periodic run-off and communication with the sea. The effect on chemistry and primary production of such physical changes as temporary isolation, changing river flows and seasonal flooding does not appear to have been investigated. Finally, the problem arises as to what happens in the case of lagoons where very high salinities are attained during the dry season. As has been discussed earlier, the total concentration of nutrient material within the lagoon should increase as the volume of water is reduced by evaporation. However, it would be expected that the increasing salinity conditions should also change the entire ecology of the lagoon. The relationship between salinity and the total standing crop of primary producers does not appear to have been investigated for this type of environment.

The above discussion illustrates the limited knowledge of the chemistry of tropical lagoons in general and of these lagoons in particular. The great variety of conditions existing in these lagoons provide an excellent opportunity to investigate the chemical processes in tropical coastal lagoons.

3. METHODS

3.1 Programme of field studies

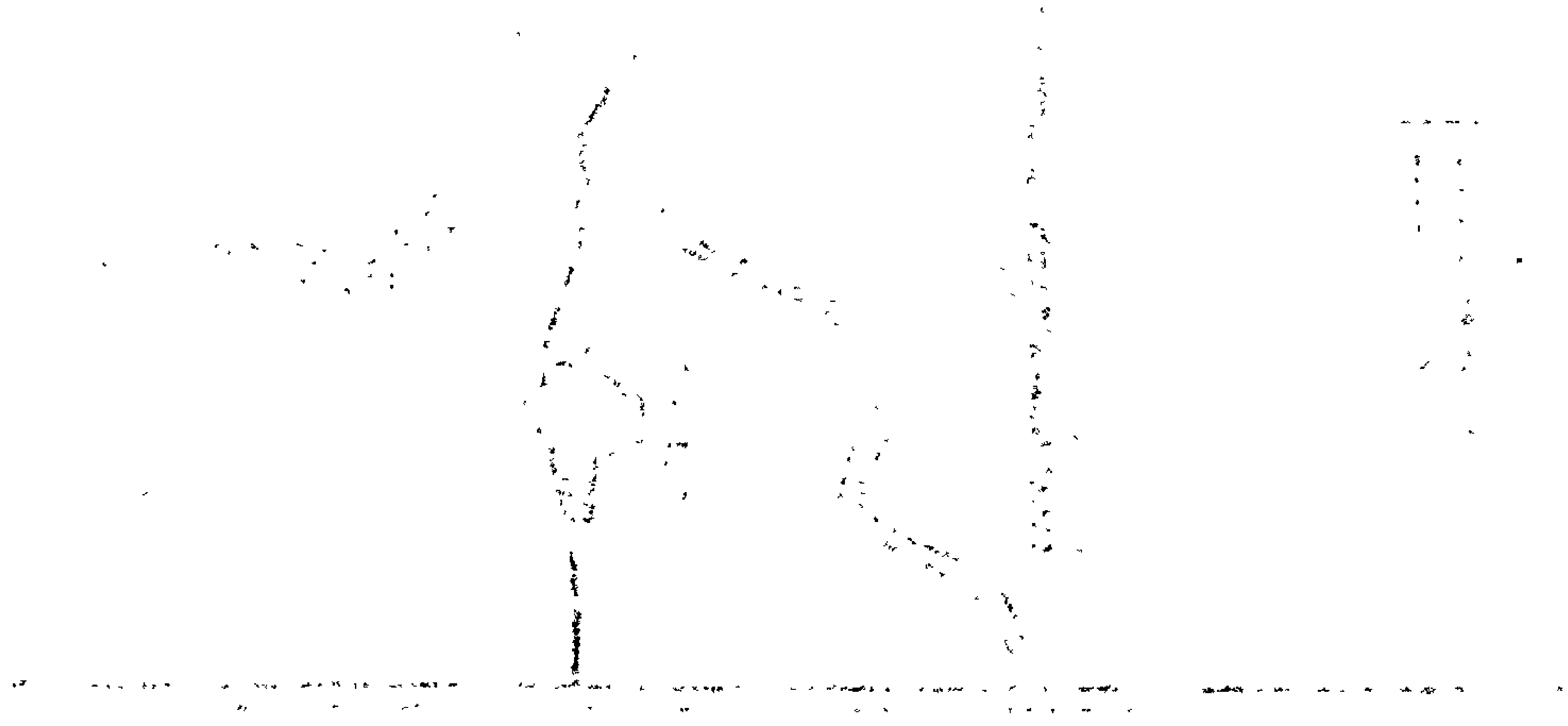
In order to establish the seasonal variations in each lagoon, it was decided to attempt one field trip per month during the period December, 1975 to January 1977. Although this proved to be slightly ambitious, a total of eleven field visits were completed, each of approximately nine days duration.

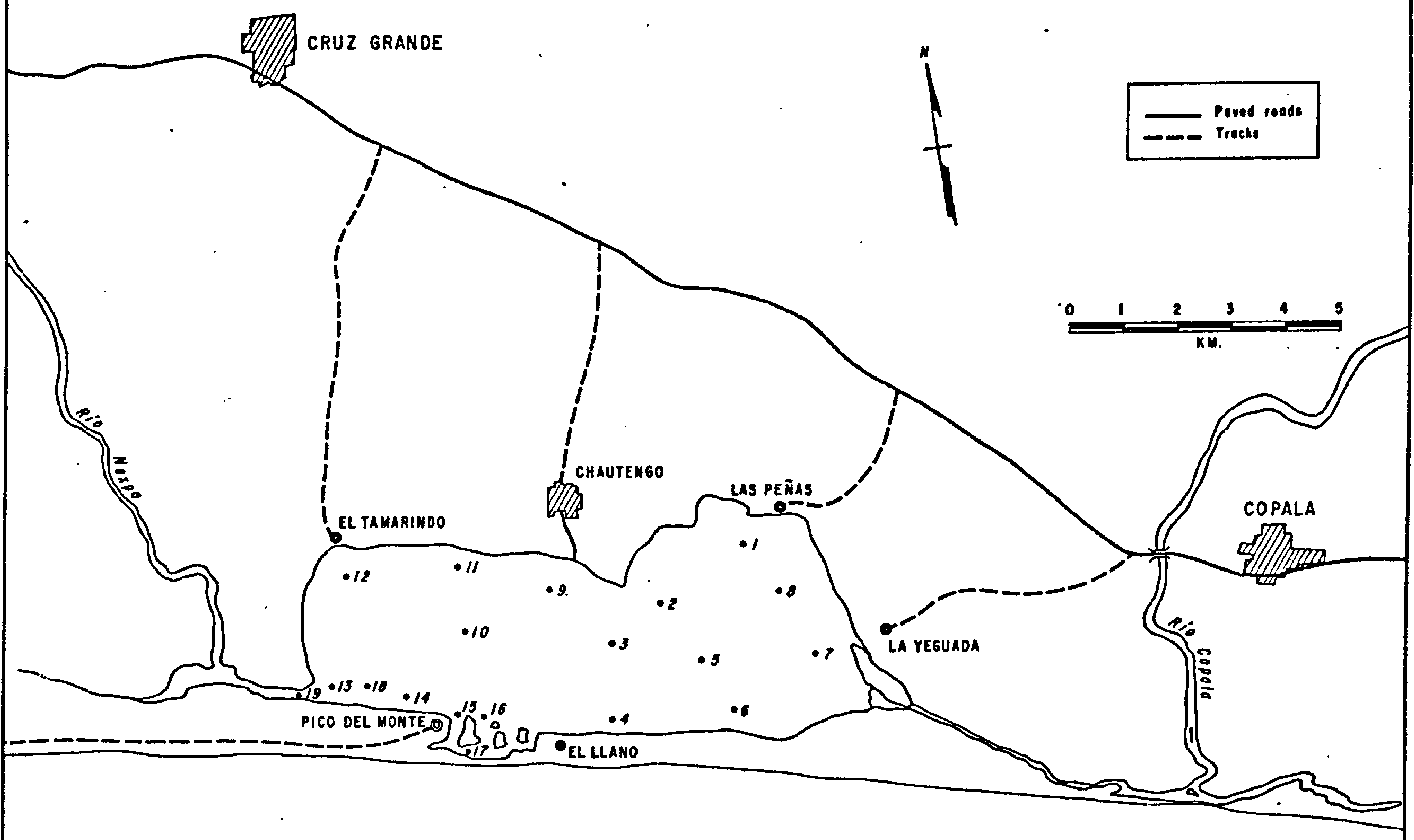
For the Laguna Chautengo and the Laguna Apozahualco a network of sampling stations was established (figs. 3.1 and 3.2 - maps from originals in the Secretaria de Recursos Hidraulicos, with modifications). The network used for Laguna Chautengo was similar to that used by Mandelli and Botello (1976) with stations 17 - 19 incorporated to permit closer examination of the Rio Nexpa. Parameters measured at each of these stations included depth, Secchi depth, salinity, temperature, oxygen, pH, alkalinity, dissolved nutrients (nitrate, nitrite, ammonia, silicate, phosphate, total phosphorus) and pigments (chlorophyll$_a$ and carotenoids). Additionally, productivity measurements were made from April 1976 at station 3 in Chautengo.

In the case of the Laguna Mitla, preliminary surveys showed both the difficulty of sampling a network of stations covering the entire lagoon and the large diurnal variations in most of the parameters measured (thus making survey results very difficult to interpret). It was decided to concentrate the field programmes on diurnal measurements in the water column at station 3 on fig. 3.3, (sketch map plotted from aerial photographs). The same parameters were considered as for the other lagoons.

Figure 3.1

LAGUNA CHAUTENGO - GENERAL MAP SHOWING SAMPLING STATIONS

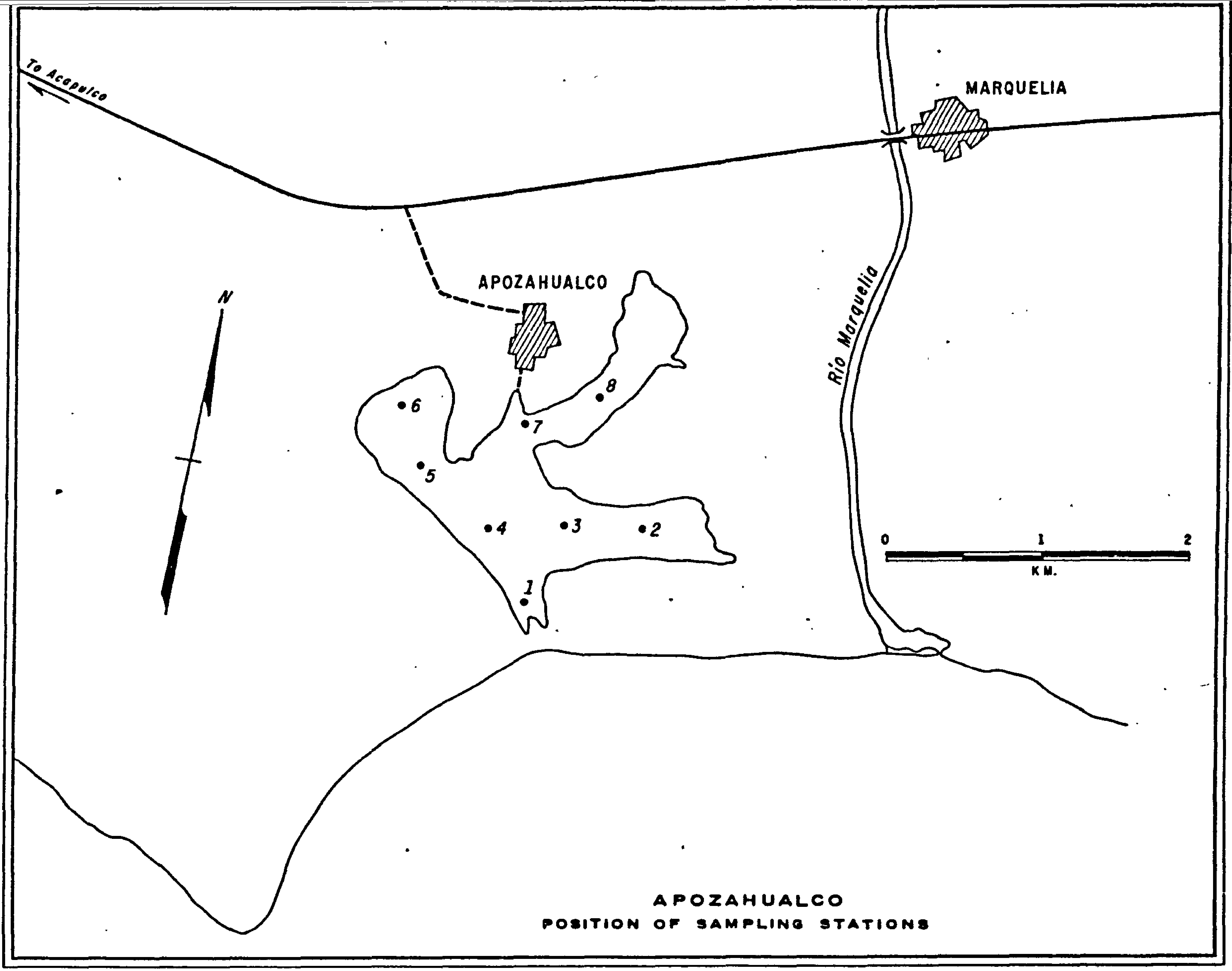




LAGUNA CHAUTENGO — POSITION OF SAMPLING STATIONS

Figure 3.2

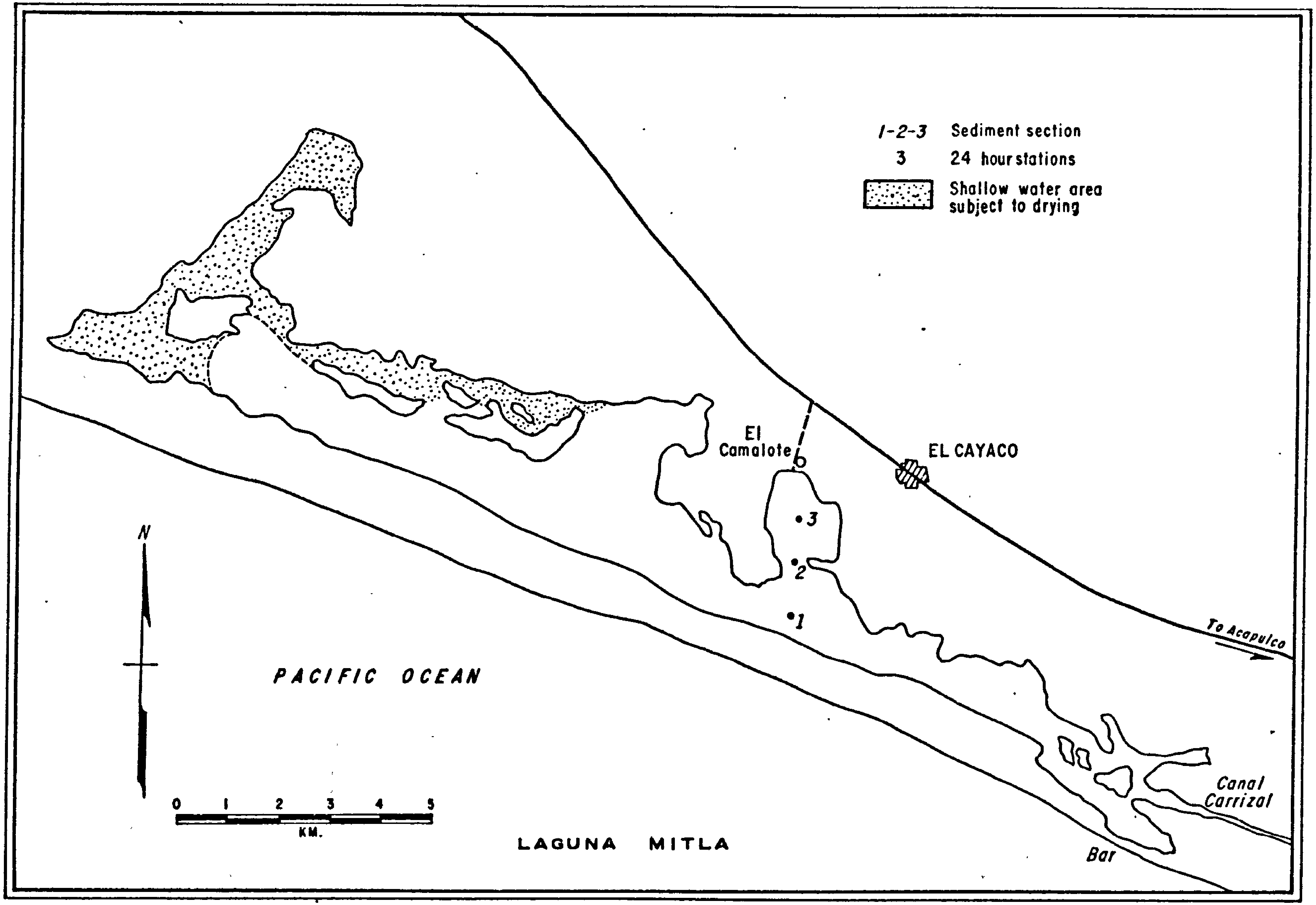
LAGUNA APOZAHUALCO - GENERAL MAP SHOWING SAMPLING STATIONS



APOZAHUALCO
POSITION OF SAMPLING STATIONS

Figure 3.3

LAGUNA MITLA - GENERAL MAP


1-2-3 Sediment section
3 24 hour stations
Shallow water area subject to drying
El Camalote
EL CAYACO
3
2
1
To Acapulco
Canal Carrizal
Bar
N
PACIFIC OCEAN
LAGUNA MITLA
0 1 2 3 4 5
KM.

Many problems were encountered in the execution of the above programme and it sometimes became necessary to make considerable amendments to it during field trips. Also additional sampling was made as each situation dictated.

3.2 Field techniques

The general programme developed for each field survey was to drive from Mexico City to Laguna Mitla (9 hours) and immediately commence a 24 hour station, with all sampling and sample processing carried out in a small boat moored at the station. The equipment and personnel would then transfer to a small hotel in San Marcos (see plate 2.1) where subsequent sample treatment was conducted. The remaining 24 hour stations were similarly conducted from a fibre-glass launch, or one occasion, a dug-out canoe, and measurements of alkalinity and oxygen were made in the relative shelter of a fisherman's hut. The final analyses of samples were carried out in Mexico City.

3.2.1 Sample collection

Samples were usually collected from a small launch or canoe fitted with an outboard motor or, where very shallow water was encountered, by wading.

Surface water samples were collected by immersing 1 litre polythene bottles. Samples from other depths were collected using a 2 litre Van Doorn sampler. A Kahlsico horizontal sampler was tested but the design is not really satisfactory as it is not completely free-flushing and probably encourages mixing. Very rudimentary sampling procedures were sometimes employed. For example, on one occasion, a 10 litre trace metal sample was taken from a depth of 5 metres by lowering a bottle weighted with a rock and manually removing the top when the bottle was in place.

3.2.2 Sample treatment

Except for oxygen samples, where the standard Winkler technique was employed, samples were taken initially in 1 litre polythene bottles. Storage of these samples (generally for no more than 2 - 3 hours) was on ice in polystyrene boxes and in the dark. The function of the chilling (which was limited to times of ice availability) was to prevent the bottles from attaining the air temperature which sometimes exceeded 40°C, and to inhibit bacterial activity. In the case of 24 hour stations filtration always immediately followed sampling.

All dissolved nutrient and alkalinity samples were pre-filtered with sample-rinsed Millipore pre-filters. Membrane filters were not generally used because of the great number required and their prohibitive cost in Mexico. In the case of Mitla samples the pre-filtered samples were further filtered using Whatman GF/C filters. These samples were not used for silicate analysis as the glass-fibre filters probably introduced contamination. Where filtration was carried out away from electricity sources, a hand pump was used.

Various techniques were employed for the preservation of dissolved nutrient samples. Dissolved phosphorus samples were stored in acid (2N H_2SO_4) washed glass bottles with *ca* 0.2 ml of 5% sodium azide/150 ml of sample (method of K.Lum - personal communication). The glass bottles were subsequently stored in the dark at room temperature. Samples for other dissolved nutrients were stored at -20°C in polythene bottles following treatment with a few drops of chloroform. For ammonia samples, this procedure was found to be at least as effective as that suggested by Degobbis (1972) in which the samples are pre-treated with alcoholic phenol.

The problem of freezing samples under tropical field conditions was overcome by the use of a large insulated chest containing about 50 kilograms of dry ice. In the few cases where this method was not possible a space was provided in the freezer of a hotel and the samples were later transferred to an ice-cream factory in Acapulco. In the case of 24 hour stations, samples were generally filtered, pre-treated and frozen within an hour of sampling.

Particulate nutrient samples were filtered onto pre-treated 4.5 cm Whatman GF/C filters. For the case of particulate carbon and nitrogen analysis, filter papers were ignited at 450°C for 3 hours in order to oxidise and remove carbon and nitrogen contaminants. For phosphorus samples, the ashed filters were subsequently washed with 1N sulphuric acid, rinsed with distilled water and dried. This procedure was to remove phosphorus compounds solubilised by the ashing procedure. All particulate nutrient samples were stored in acid washed glass sample tubes in deep-freeze conditions.

Particulate samples to be analysed for pigments were filtered onto 4.5 cm Whatman GF/C filters. Before sample filtration, the filter surface was coated with magnesium carbonate by filtering approximately 25 ml of water to which was added 2 ml of 1% $MgCO_3$ suspension (Strickland and Parsons 1968). Pigment samples were stored in open tubes, sealed within a plastic box containing a bag of silica gel. The whole box was immediately placed in deep-freeze conditions. The function of the silica gel was to prevent excess water freezing around the filter papers.

Trace metal samples were taken in 10 litre hard polythene bottles and transferred without pre-treatment to the laboratory in Mexico City where they were filtered using pre-washed 0.45 µm membrane filters. This procedure often required several filters owing to the large quantity of suspended material in the samples.

3.2.3 In-situ studies

In-situ measurements included depth, Secchi depth, wind velocity, humidity, salinity and temperature. Depth was measured using a calibrated sounding-pole or a lead line. Secchi depth was measured using a small improvised Secchi disc. A small hand-held anemometer was used for wind velocity measurements. For air temperature and humidity, a direct reading thermometer/hygrometer (Bacharach Instrument Co) was employed. Salinity and water temperature were measured using a laboratory calibrated N.I.O. MC5 salinometer (Electronic Switchgear Ltd).

For oxygen measurements, a Yellow Springs Instruments polarographic oxygen meter was used. This was air calibrated according to the makers instructions. The instrument was found to be very stable and reliable and results compared very well with those obtained from the Winkler method.

3.2.4 Sediment collection and treatment

Surface sediments were collected by hand using a 15 cm plastic tube into which a wooden plunger was inserted. The samples were immediately sealed in polythene bags and frozen.

Sediment cores were taken using a specially built Mackereth piston corer (Mackereth 1971). The cores taken were immediately extracted using a long handled piston and not by the method recommended in the original paper. Cores were extracted and sampled as each station was completed. The cores were cut into 10 cm sections stored in polythene bags and frozen, unless immediately required for further treatment. Where pore water samples were required the samples were taken to a nearby fisheries technology school where a small centrifuge was set up. Pore water was extracted by centrifugation and its pH immediately measured using a Pye-Unicam portable pH meter. The samples were then transferred to small pre-washed polythene bottles, treated with two drops of chloroform and frozen.

3.3 Analytical methods

3.3.1 Salinity, pH and Alkalinity

Salinity was determined in the laboratory using a Beckman inductive salinometer standardised with Copenhagen standard sea-water. A sub-standard was prepared from Gulf of Mexico surface water and this was used to calibrate the portable salinometer (see 3.2.3).

pH measurements were made using a Pye-Unicam portable pH meter. Alkalinities were determined using the method of Anderson and Robinson (1946) and the tables given by Strickland and Parsons (1968). This method was often very unsatisfactory owing to the salinities and pH measurements being well beyond the range for which it was originally designed. For future studies, the use of potentiometric titrations is recommended (using a glass electrode and stepwise addition of dilute acid).

3.3.2 Micronutrients

After January 1976, a Technicon CSM 6. 6-channel auto-analyser became available in Mexico City. This was set up to examine the following parameters:- silicate, nitrate + nitrite, nitrite, ammonia and reactive phosphate. Analysis of reactive phosphate was generally conducted using a manual method as this proved to be the most convenient technique for the wide range of salinities encountered.

Silicates

Silicates were determined using the method of Brewer and Riley (1966). In this method a molybdenum blue complex is formed following reaction of dissolved silicate in the sample with ammonium molybdate to produce a B-silicomolybdic acid and the subsequent reduction of this using metol-sodium sulphite solution (in the presence of oxalic acid to remove interfering phosphate). The complex was measured at 815 nm.

Nitrite and Nitrate

Nitrate + Nitrite was determined by the method of Brewer and Riley (1965). In this method nitrate is reduced to nitrite by a cadmium column, the resulting nitrite being complexed as an azo dye and measured at 540 nm. Nitrite was determined using the same basic method, but without the use of the cadmium reductor column. For the large range of salinity encountered, it was found necessary to group samples of similar salinities and run them on the autoanalyser, using standards and washes of synthetic sea water (Strickland and Parsons 1968) made up to the appropriate salinity.

Ammonia

The determination of ammonia was made using the method of Grasshoff and Johannsen (1972). This method relies on the production of a blue indophenol dye (measured at 640 nm) by the reaction (at 75°C) of the ammonia with sodium hypochlorite and phenol in the presence of a sodium nitroprusside catalyst. A lower temperature (50°C) was used for this reaction in the present study.

Whilst this method yielded very reproducible results, it suffers from interferences by amino acids and urea. Though this effect has been considered 'unimportant' by the original authors, a reassessment of the interferences revealed that, even at the reduced temperature used in the present study, 20% of urea and 10% of alanine was detected as ammonia. This effect may be of limited importance in the open-ocean situation. However, in coastal waters, significant concentrations of the interfering substances may be present, especially where ammonia concentrations are very low.

Reactive Phosphate

Reactive phosphate was determined using the method of Murphy and Riley (1962). This method has the advantage of being very simple (requiring only one reagent solution) and very rapid. In a few samples it was found that after initial development of the colour a very gradual increase continued for several hours, possibly resulting from hydrolysis of organic compounds. It was thus decided to measure all samples 15-20 minutes after the reagent addition in order to standardise the reaction conditions. This time period was selected as the time at which the initial rapid colour development was completed and a negligible amount of organic material had been hydrolysed.

Total dissolved Phosphorus

Total phosphorus was measured as ortho-phosphate following wet oxidation of the samples with a mixture of 0.5g potassium persulphate and 0.5 ml of 50% sulphuric acid/ 50 ml sample. The reaction was carried out at 120°C for ½ hour in an autoclave (Inland Water Directorate 1974). The ortho-phosphate was measured by the single solution method described above, but leaving the colour to develop for 1 hour before measuring. Slower colour development was often a result of the more acidic conditions. Almost immediate colour development is obtained if the reagent is added while the autoclaved sample is still warm.

3.3.3 Particulate Nutrients

Carbon and Nitrogen

Carbon and nitrogen were determined simultaneously using a Perkin-Elmer CNH elemental analyser (Inland Water Directorate 1975). In this method, the 4.5 cm GF/C filters holding the particulate material are coated with manganese dioxide, rolled up and pushed into a purpose built holder which is subsequently inserted in the furnace of the analyser.

Phosphorus

Particulate phosphorus was determined by an adaption of the total dissolved phosphorus method described above. The sample, filtered onto a GF/C filter (see earlier), was immersed in 50 ml of distilled water contained in a 100 ml pyrex measuring cylinder. The potassium persulphate - sulphuric acid reagents were added (as for the analysis of total dissolved phosphorus) and a pyrex beaker inverted over the cylinder. Batches of cylinders were then autoclaved as in the total dissolved phosphorus method, and the orthophosphate reagent added. Phosphate was determined spectrophotometrically at 885 nm following colour development and centrifugation.

This method has several advantages over that recommended by Strickland and Parsons (1968). Since the reaction conditions are carefully controlled and a large batch of samples may be analysed, the method is more rapidly performed, easier to standardise and involves less risk of contamination. Furthermore, in the Strickland and Parsons (1968) procedure, it is necessary to distill off all the perchloric acid used as the oxidant, since it oxidises the ascorbic acid in the mixed reagent, inhibiting colour formation. Where this step is incomplete, the reproducibility of analyses is very poor. This entire procedure is avoided by the present method.

3.3.4 Pigments

Chlorophyll$_a$ (together with phaeophytin$_a$) was determined and carotenoids estimated, by a modification of the Richards and Thompson (1952) trichromatic method.

Filters containing samples and magnesium carbonate (see earlier) were treated with a 90% acetone/water solution in glass test-tubes protected from the light. The tubes were maintained overnight in a refrigerator to permit the extraction of pigments to proceed. The following day the extraction process was completed by thoroughly breaking-up the filters with a glass rod. The contents of the tube were then transferred into a filter tube which consisted of a drawn-out test-tube with a small plug of glass wool inserted into its narrowest part. A small hand pump was used to force the pigment extract (together with a 90% acetone wash) through the tube into a measuring cylinder. Following measurement of the extract volume, it was centrifuged and measured spectrophotometrically (Strickland and Parsons 1968). Pigment concentrations were calculated from the formulae of Parsons and Strickland (1963).

The modified method presented above is very simple to use and has the advantage of producing very low blanks without the need for an extended period of centrifugation.

3.3.5 Trace metals

Dissolved trace metals were determined by atomic adsorption spectrophotometry following preconcentration on Chelex resin columns (Riley and Taylor, 1968, modified Abdullah and Royle 1971). Water used for filter washing and dilution of acids, samples and standards was purified from distilled water by passing it through a double column of chelex resin in the ammonium form.

3.3.6 Sediment analysis

Frozen sediment samples returned to the laboratory were thawed and sub-samples taken for the determination of water content by weight loss after drying to constant weight at 60°C, and ignition loss by further heating the dry sample at 650°C for three hours. The remaining part of the samples were lyophilised and stored in polythene bags. A large subsample was taken from each bag, ground to a fine powder and homogenised in a porcelain mortar. This sample was then analysed for the following parameters :-

Carbon and Nitrogen

Samples were analysed using a Perkin-Elmer CNH analyser (Inland Water Directorate 1975). Before analysis, the samples were treated with warm 0.2.N. HCL in order to remove carbonate compounds, washed with distilled water and dried. This procedure is probably the greatest source of error in the method, since other components of the sediment sample may be solubilised and the 'carbonate free' weight, used before submitting the sample to analysis, is probably an under-estimation of that actually found in the sediment.

Phosphorus

The method used was that quoted by Aspila et al (1976). The sample was dry ashed at 600°C and leached with dilute hydrochloric acid. Phosphate was then determined on the acid solution by the single solution method described earlier. It is very important to regulate the amount of acid used in this method as a strongly acidic sample inhibits the formation of the molybdenum blue complex. This effect is discussed in detail in the paper cited.

Carbonate

Carbonates were estimated as calcium carbonate using a simple volumetric technique. A weighed amount of sample was placed in a beaker with an aliquot of 0.2 N HCL and warmed gently. When the evolution of bubbles had ceased the mixture was centrifuged and the centrifugate, together with two distilled water washings, was transferred to a conical flask and back titrated with dilute sodium hydroxide using phenolphthalein indicator.

This method is very simple to use but is sensitive to other alkaline components in the sediments (e.g. Hydroxides, borates and sulphides). Where large quantities of carbonate are encountered it provides a reasonable estimate. In practice, the method was generally employed in sediments with a carbonate content of more than 5%.

Interstitial water analysis

Interstitial water was collected by the method outlined earlier. The interstitial water samples obtained were diluted and filtered and the nitrate, nitrite, ammonia, phosphate and total phosphorus were determined by the methods described earlier. Salinity determinations were made using a small hand-held temperature compensated refractometer.

3.4 Studies of primary productivity

Primary productivity was studied by two different methods; observation of diurnal oxygen changes and tracer uptake experiments with ^{14}C. Whilst the former method was designed to provide an estimate of gross primary productivity and regeneration, the latter was intended to demonstrate the variations in primary productivity during the day and with depth in the water column.

3.4.1 Oxygen production and respiration

Oxygen, temperature and salinity measurements were made from a moored boat at 2-3 hourly intervals and at one metre increments of depth throughout the water column for a 24 hour period. Gross productivity and respiration was calculated from this data using the method of Odum (1960), and for the special case of Mitla, using a modified version of the Odum method. A full discussion of these methods is presented in Appendix 2. Values for productivity and respiration were presented as g O_2/m^2/day and not converted to carbon productivities. This was because conversion factors have not been well established for the type of plant communities found in these environments.

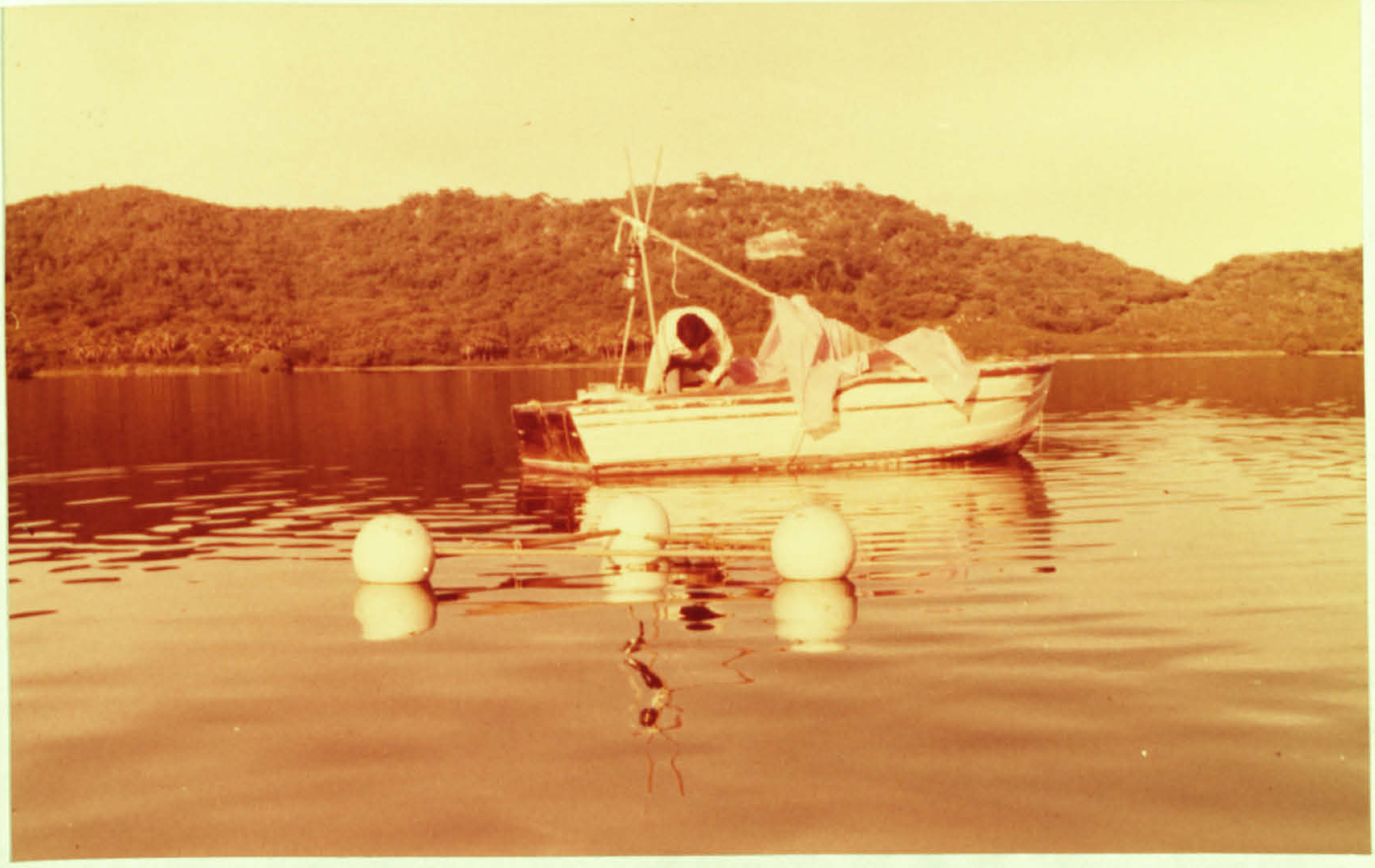
3.4.2 ^{14}C fixation

The method used for ^{14}C studies was a modification of the well-established 'light and dark bottle' productivity method (Steeman-Nielsen 1952, modified by Strickland and Parsons 1968). The method was applied as follows:-

A number of 29 ml cylindrical glass crew-cap bottles were prepared each with two small pieces of galvanised iron wire

Plate 3.1

SURFACT FLOAT AND SURVEY BOAT, LAGUNA MITLA PRODUCTIVITY STATION.



hour after which the bottles were quickly detached from the suspending cord and wrapped with aluminium foil. Starting with the bottom 'light' bottle, the bottles were opened and a 10 ml sample was drawn into a 10 ml disposable syringe. This was then connected to a 25 mm plastic Swinnex filter holder containing a 25 mm 0.45 µm membrane filter and the sample was filtered using gentle pressure on the syringe. This was followed by two 5 ml distilled water washes and a 5 ml volume of air to remove water trapped in the filter holder. The filter was then removed and placed in a screw-cap scintillation vial which was immediately transferred to a chest of dry ice. The time taken to complete the filtration and sample storage for the entire bottle cast was between four and five minutes. During the exposure period samples were taken for alkalinity and pigment determinations.

On return to the laboratory, 10 ml of 'Bray' liquid scintillation solution was added to each of the vials. When the filters had completely dissolved, the vials were counted in a Packard Tri-Carb scintillation counter for four minutes using automatic internal standardisation. The internal standardisation was checked with a toluene ^{14}C standard. For sample counting, the general counting efficiency of the machine was between 51% and 56%. The total ^{14}C activity of the sample was calculated and the rate of photosynthesis estimated from the formulae given by Strickland and Parsons (1968).

The method described above has several advantages over that given by Strickland and Parsons (1968). The small bottles used enable productivity to be measured in lagoons with a very dense population of primary producers without the need for large quantities of radiocarbon. The handling of samples is reduced to a minimum and the pressure filtration technique enables immediate filtration of samples to be performed in a canoe or small launch. Scintillation counting of the samples reduces self-absorption effects and the absorption of β-radiation by suspended particulate matter - important factors in direct Geiger - counting procedures.

Reproducibility of duplicate measurements was of the order of ± 5%. An experiment was conducted to compare the effect on productivity measurements of changing the exposure period of the samples from 1 hour to ½ hour. Results (Table Pl. Appendix 1) show an average difference between productivity measurements for equal depths and at the same time of day as ± 24%. This difference probably partly results from two sources. The first is that the effect of any light exposure during sample handling is proportionally greater during the shorter exposure time, (3 minutes of light exposure could produce a 10% error in the half-hour measurement of surface productivity). The second is that experiments were conducted under natural light conditions and the intensity variations during the two periods may have produced significant differences in the rate of carbon fixation in the two groups of samples. The similarity between the half hour and hour values in the experiment also suggests that the same parameter is being measured. This is usually assumed to be a measure of the net productivity during the measurement period.

Values of productivity for each depth were plotted as daytime curves. These curves were then integrated to give the total daily net productivity for each of the depths chosen.

Integration of these values with depth gave an approximate estimate of the total daily primary productivity for the station. The accuracy of this estimate clearly depends on the number of measurements made, both with time and depth. Depth profiles for the present study may not have included some subsurface productivity maxima and estimated values are probably low, both from this effect and from the effect of sample enclosure and shading. Whilst this method is of limited use for productivity measurements, it has a considerable advantage over the oxygen method in that it shows the pattern of productivity with respect to time and depth in the water column.

4. Results

4.1 Lagoons selected for study

It was decided to choose lagoons representative of each of the groups presented in Chapter 2. The lagoons selected were the Lagunas Chautengo, Apozahualco and Mitla. Maps of these lagoons are presented in figs. 3.1, 3.2 and 3.3.

4.2 Presentation of data

Data tables are presented in Appendix 1. The tables are arranged in the following order : Tables C1 - 13 and A1 - 8 show seasonal variations in chemical and physical parameters in Chautengo and Apozahualco respectively; Tables C14 - 16 and M1 - 6 are records of 24 hour stations in Chautengo and Mitla respectively; Tables P1 - 9 are results of productivity experiments and Tables S1 - 2 present chemical analysis of sediments and interstitial waters.

Minimum detection limits of chemical analyses are generally as shown in the manual of Strickland and Parsons (1968). However, these limits, which are based on manual methods did not always apply to the automated ones, especially where an irregular base-line on the auto-analyser chart recorder made it difficult to interpret very small analytical peaks. Detection limits for dissolved nutrient analyses were generally as follows :-

Table 4.1 - Comparison of the mean surface values of some chemical parameters in the present study with previous studies in tropical lagoons.

PARAMETER		Present Study			Mandelli & Botello (1976)		Venezuelan tropical lagoons	
		Chautengo	Apozahualco	Mitla	Chautengo	Mitla	Bonilla & Benitez (1972)	Okuda *et al* (1965)
Salinity °/oo	MEAN	16.5	46.9	-	9.9	3.37	38.3	42.3
	Range	0.0 - 33.45	14.1 - 118.0	2.25 - 4.1				
	S. Dev.	7.75	31.2	-				
Reactive Phosphate µg at P l^{-1}	MEAN	1.68	2.2	0.31	1.62	-	0.32	0.48
	Range	0.55 - 5.0	0.64 - 6.5	0.22 - 0.41				
	S. Dev.	0.75	1.4	0.08				
Total dissolved Phosphorus µg at P l^{-1}	MEAN	2.53	2.8	-	2.24	-	-	-
	Range	1.1 - 5.2	1.02 - 6.5	-				
	S. Dev.	0.90	1.8	-				
NH_4^+ µg at N l^{-1}	MEAN	1.3	2.8	1.0	7.8	2.23	3.6	18.8
	Range	<0.2 - 20.0	0.4 - 7.7	0.5 - 1.3				
	S. Dev.	2.9	3.3	0.3				
NO_3^- µg at N l^{-1}	MEAN	0.51	0.51	<0.05	0.39	0.24	1.2	1.74
	Range	0.05 - 10.9	-	-				
	S. Dev.	2.0	-	-				
NO_2^- µg at N l^{-1}	MEAN	0.06	<0.02	<0.02	0.14	0.29	0.05	0.34
	Range	<0.02 - 1.3	-	-				
	S. Dev.	0.19	-	-				
Dissolved organic N µg at N l^{-1}	MEAN	-	-	-	-	-	17.8	23.2
Silicate µg at Si l^{-1}	MEAN	103.	-	250	-	-	-	-
	Range	3. - 230.	0.1 - 20.0	-				
	S. Dev	51.5	-	-				
Chlorophyll a mg m^{-3}	MEAN	16.1	20.6	121.0	-	-	-	-
	Range	1.22 - 121.5	0.5 - 87.8	44.8 - 171.0				
	S. Dev.	21.0	21.9	53.1				
Net Productivity g C/m^2 / day	MEAN	0.72	-	2.3	-	-	-	-
	Range	0.32 - 1.4	-	1.1 - 2.8				
	S. Dev.	0.5	-	0.8				

Mexican lagoons and the concentration order for all lagoons presented is $NH_4^+ > NO_3^- > NO_2^-$. The mean concentration of nitrate in Chautengo was inflated by some very high values at the start of the rainy season and for most of the year the nitrate level was below the minimum level for analysis. The large variability of dissolved inorganic nitrogen is illustrated by high standard deviations (with respect to mean concentrations) of results from the three lagoons studied. Conversely, phosphorus analyses for the three lagoons show a more even distribution with a relatively small standard deviation from the mean. Phosphorus concentrations were similar for Chautengo and Apozahualco but much lower for Mitla. The values quoted for Mitla were similar to the Venezuelan examples, although their other characteristics (salinity, nitrogen nutrients) were incomparable. Silicate concentrations in the Guerrero lagoons appear to have some inverse relationship to salinity values. Both factors are probably related to isolation. Apozahualco, the lagoon most isolated from river inputs of silicate and subjected to flushing from the sea has the highest salinity and lowest silicate concentration. Mitla, the lagoon most isolated from sea water exchange has the lowest salinity and highest silicate concentration, since the small river input of silicate is not accompanied by a loss to the sea. Measurements of salinity, phosphorus nutrients, nitrite and nitrate (Chautengo) are very similar to those presented by Mandelli and Botello (1976). However, significant differences are observed for ammonia and for nitrate analyses in Mitla. The higher values obtained for the earlier study may reflect the longer storage time of the samples before filtration, allowing more time for breakdown of some of the

4.2 - Overall seasonal variations in the Laguna Chautengo

Month	Date	Mean Depth m	Mean Salinity °/oo	Reactive Phosphate µg at P l^{-1}	Total Dissolved Phosphorus µg at P l^{-1}	Silicate µg at Sil^{-1}	NH_4^+ µg at N l^{-1}	NO_3^- µg at N l^{-1}	NO_2^- µg at N l^{-1}	Chlorophyll$_a$ mgm^{-3}
Jan.	16	0.77	19.51	1.64	2.78	104.	-	-	-	8.7
March	2	0.75	19.86	2.7	3.0	-	-	-	-	-
April	4	0.68	27.15	1.6	2.85	75.	-	-	-	15.7
May	10	0.60	25.14	1.71	2.30	102.	1.3	<0.1	<0.05	16.7
June	16	1.45	10.33	1.62	3.18	117.	1.4	1.2	0.16	59.3
July	18	1.02	18.56	1.37	2.69	51.	2.3	1.0	0.04	10.1
Sep.	13	1.02	15.42	1.73	2.06	153.	-	-	-	9.2
Nov.	1	0.04	11.35	1.18	1.77	120.	0.6	0.1	0.05	4.3
Dec.	9	0.92	19.64	1.37	2.02	100.	0.2	0.2	0.04	3.5

4.3 - Overall seasonal variations in the Laguna Apozahualco

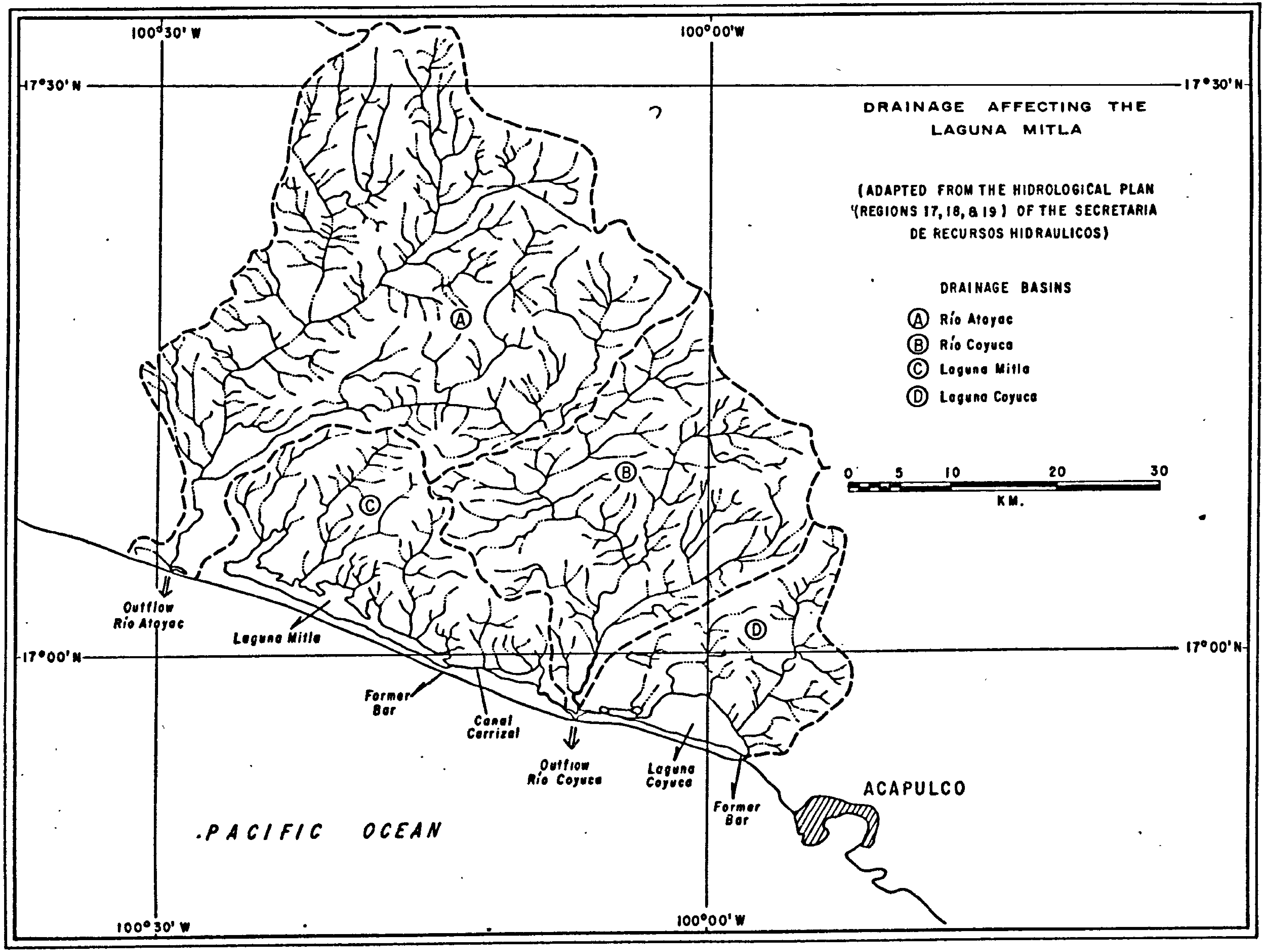
Month	Date	Mean Salinity °/oo	Reactive Phosphate µg at P l^{-1}	Total Dissolved Phosphorus µg at P l^{-1}	NH_4^+ µg at N l^{+}	Chlorophyll mg m^{-3}
Nov.	29 (1975)	29.44	2.47	2.92	-	5.9
Jan.	15	40.71	3.21	4.48	-	10.6
Feb.	29	59.6	-	-	-	19.7
April	6	81.2	3.80	6.42	-	77.7
May	9	118.0	4.38	-	-	17.8
June	15	14.1	1.1	1.90	0.45	47.3
July	17	27.8	1.0	1.5	2.0	2.5
Sep.	11	34.48	2.44	3.05	7.7	14.7
Oct.	31	31.8	0.78	1.17	1.1	4.9
Dec.	8	32.1	-	-	-	-

organic and particulate material.

Seasonal variations in the mean concentrations of dissolved nutrients, pigments and salinity are shown in Tables 4.2 (Chautengo) and 4.3 (Apozahualco). Mean nutrient values are calculated by multiplying the mean concentration for each station with the respective depth, summing these values and finally dividing by the sum of the depths of all the stations used. Mean values of salinity for each station (see Appendix 1) were obtained by integration of the salinity profiles where stratification was observed. The overall mean for the salinity was obtained from these values in the same manner as the mean nutrient values.

FIGURE 5.1

DRAINAGE AFFECTING THE LAGUNA MITLA.

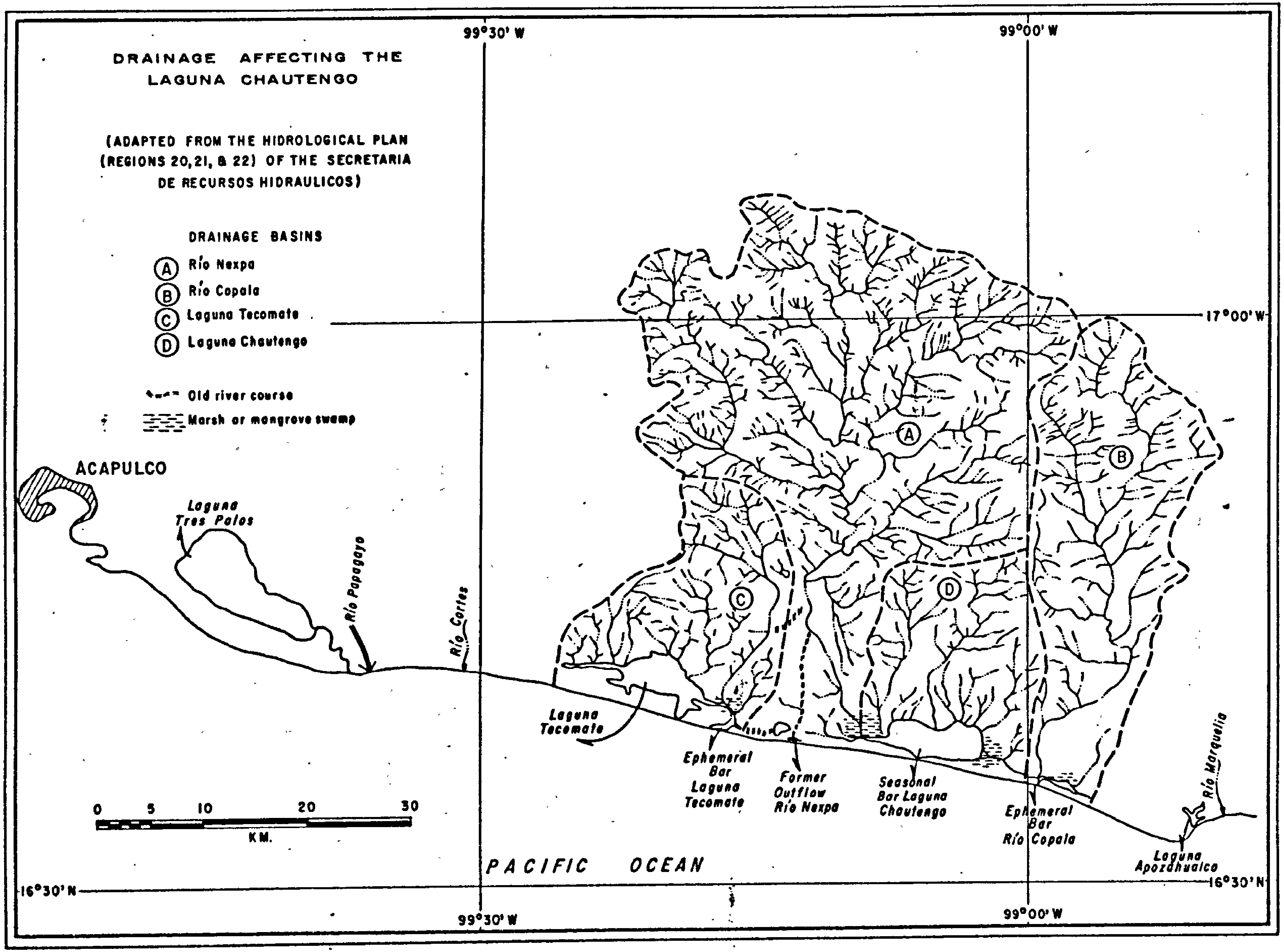


DRAINAGE AFFECTING THE LAGUNA MITLA

(ADAPTED FROM THE HIDROLOGICAL PLAN (REGIONS 17, 18, & 19) OF THE SECRETARIA DE RECURSOS HIDRAULICOS)

Figure 5.2

DRAINAGE AFFECTING THE LAGUNA CHAUTENGO.



DRAINAGE AFFECTING THE LAGUNA CHAUTENGO

(ADAPTED FROM THE HIDROLOGICAL PLAN (REGIONS 20,21, & 22) OF THE SECRETARIA DE RECURSOS HIDRAULICOS) through the mangrove channels is probably from the lagoon to the river-bar, delaying the time at which the lagoon directly opens to the sea. No information is available on the drainage affecting the Laguna Apozahualco. The immediate drainage basin appears to be very small and there is no communication with the nearby Rio Marquelia, except in severe floods (such as occurred in October 1976).

A description of the basic hydrographical changes which took place in the seasonally 'opening and closing' lagoons is illustrated by considering the variations in mean salinity (Table 5.1). Following the bar closure, the salinities of both lagoons showed increases due to evaporation. In the case of Laguna Apozahualco, the salinity reached $118^{\circ}/_{oo}$ in May and small evaporation ponds were dug by the local population to collect crystalline salt.

With the start of the rainy season in June, the lagoons were rapidly filled to levels well above that of the sea. The salt content was strongly diluted (2.4 times for the case of Chautengo and 8.4 times for the case of Apozahualco) and low-lying land surrounding the lagoons was flooded. Both lagoons opened to the sea in the first week of July. Laguna Chautengo was opened mechanically because it was starting to open dangerously close to some construction work on the bar. Following a period of water discharge across the bar, tidal exchange processes increased the salinities of both lagoons to their July values. The lack of run-off into the Laguna Apozahualco resulted in the bar reclosing in August. Heavy rainfall, coupled with flooding from the Rio Marquelia caused the bar to open again in October and it finally

Table 5.1 - Seasonal salinity variations in two lagoons

Survey Period	Laguna Chautengo		Laguna Apozahualco	
	Salinity $^{o}/_{oo}$	Sea Inlet	Salinity $^{o}/_{oo}$	Sea Inlet
Nov. 29 (1975)	-	Open	29.44	Closed
Jan.15-16 (1976)	19.51	Open	40.71	Closed
Feb.29 - Mar. 2	19.86	Closed	59.55	Closed
April 4 - 6	22.15	Closed	81.2	Closed
May 9 - 10	25.14	Closed	118.0	Closed
June 15 - 16	10.33	Closed	14.1	Closed
July 17 - 18	18.56	Open	27.5	Open
Sep. 11 - 13	15.42	Open	34.5	Closed
Oct. 31 - Nov. 1	11.35	Open	31.8	Open
Dec. 8 - 9	19.64	Open	32.1	Open

closed in late December. The bar of the Laguna Chautengo remained open throughout this period, probably as a result of continuous river input from the Rios Nexpa and Copala. The bar finally closed in March 1977.

These general observations are very similar to those of Mandelli and Botello (1976) for the previous year. They described the Laguna Chautengo as having an annual cycle of four stages :

I. Bar closure and a period where evaporation exceeds run-off.

II A period where heavy precipitation causes the lagoon to be refilled.

III The bar opens and the lagoon discharges to the sea.

IV A period of tidal exchange together with river discharge into the lagoon.

Evaporation during the first stage of the lagoon cycle, may be estimated from the salinity changes during the period of lagoon isolation. The data (Table 5.1) gives mean salinity values for successive months. Since it is difficult to measure with great precision, the change in the mean depth of the lagoon from one month to another (the station grid would need to be precisely located), an indirect method was employed, based on one mean depth and the salinity change. If the total salt is conservative.

$$S_1 \; V_1 \; \delta_1 \quad = \quad S_2 \; V_2 \; \delta_2$$

Where S is the salinity at times 1 and 2 respectively δ is the specific gravity and V the lagoon volume.

For Chautengo the annual change in surface area of the lagoon is small. Hence :

$$S_1 \; d_1 \; \delta_1 \;=\; S_2 \; d_2 \; \delta_2$$

Where d is the depth.

It follows that the net evaporation rate E over time period T is given by :-

$$E = \frac{d_1 - \left(d_1 \times \frac{S_1 \delta_1}{S_2 \delta_2}\right)}{T}$$

Net evaporation estimates are given on Table 5.2 for the period during which the lagoon was isolated from the sea. The evaporation data shown is for the period when river input into the lagoon was reduced to a small stream along the Rio Copala.

Table 5.2 - Estimation of evaporation from the Laguna Chautengo

Period	Daily Net Evaporation Rate mm/day	Total Daily Net Evaporation m^3
Mar - Apr.	2.2	8.1×10^4
Apr - May	2.3	8.5×10^4

During the first weeks of the rainy season the lagoon volumes rapidly increased due to direct precipitation and run-off from the catchment area immediately adjacent to the lagoon, there being an initial lag between the first rains and a large river flow due to the soaking effect. This is well illustrated for the case of Chautengo, where an approximate water budget may be presented for the period from 10th May to 16th June 1976 :-

1)	Run-off from Rio Nexpa, measured as	+	$5.5 \times 10^6 m^3$ (16%)
2)	Run-off from Rio Copala, estimated as	+	$2.3 \times 10^6 m^3$ (7%)
3)	Evaporation, estimated as	-	$3.1 \times 10^6 m^3$
	Total		4.7×10^6
4)	Total increase in water volume, measured as		$3.1 \times 10^7 m^3$
	Difference, assumed to be direct precipitation and immediate run-off		$2.6 \times 10^7 m^3$ (77%)

Figures in parenthesis indicate the contribution of each of 1) 2) and 4) to the total increase in water volume.

Sources of information are (1) Measurements made by the Secretaria de Recursos Hidraulicos, (2) Estimation from (1) by comparison of the catchment areas of the two rivers, (3) Table 5.2, May data, (4) Mean depth changes from field surveys.

It can be seen that during this initial period direct precipitation and immediate run-off are the most important sources of water supply to the lagoon. It seems reasonable to suppose that dissolved substances might also be transported by the same processes.

On bar opening, there was a large discharge of lagoon water (together with dissolved and suspended substances) to the sea. From the change in the mean depth of the lagoon between the June and July surveys, it is possible to calculate that the discharge to the sea was at least 40% of the June volume (some $2.5 \times 10^7 m^3$).

Following the opening of the bar the lagoon water levels quickly equilibrated with that of the sea. This can be seen in diagram (i) of fig. 5.3. The water level of Chautengo is shown to vary during the 'bar open' period according to the annual cycle of offshore mean tide level (diagram (ii)). These variations have the effect of reducing the January 1977 mean volume of the lagoon to about 80% of its July value. Diagram (i) also illustrates the effect of evaporation and refilling on the depth of the lagoon during the 'bar closed' period.

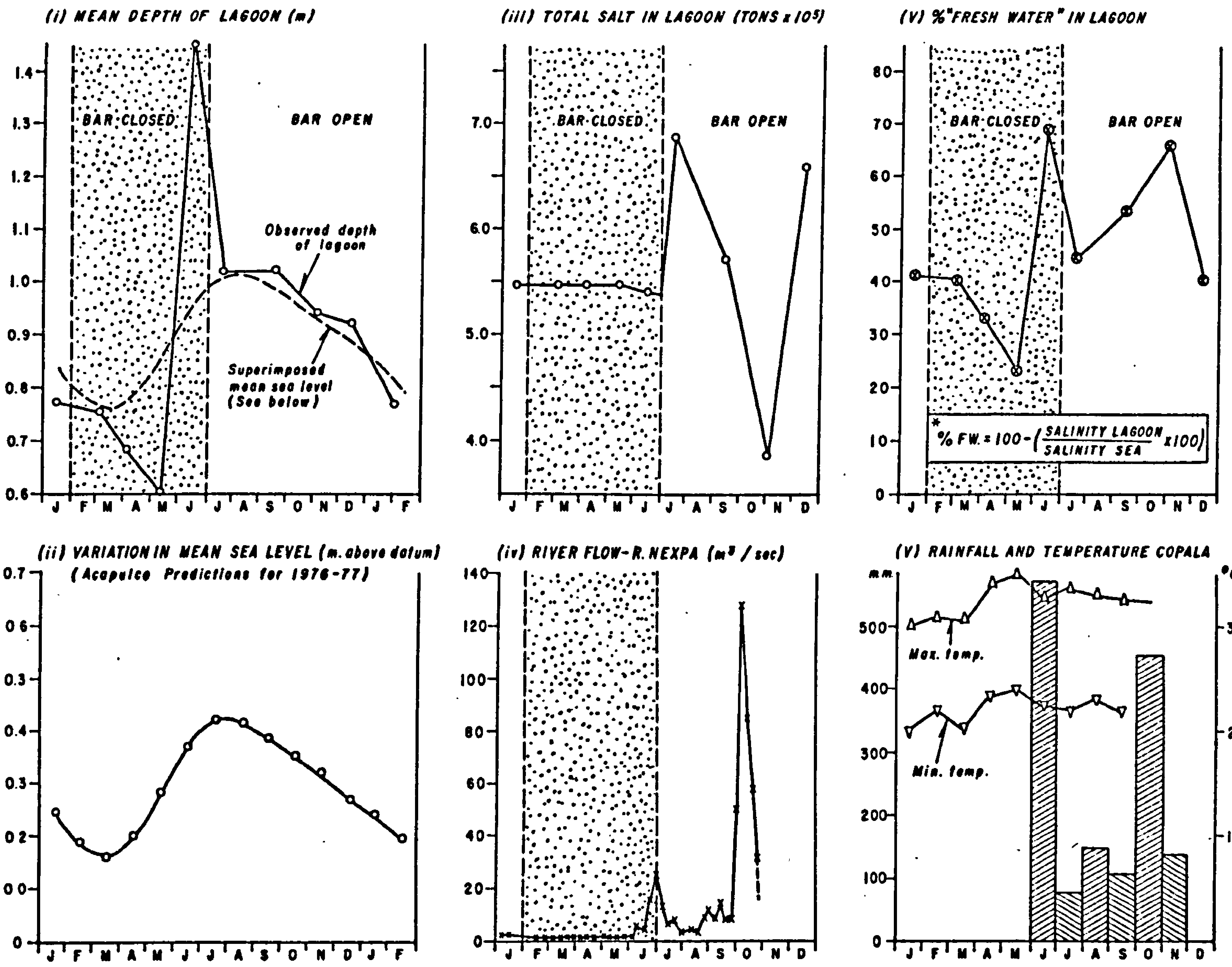
The effect of input and tidal exchange on the resultant lagoon salinity is illustrated for the case of Chautengo by diagrams (iii) to (v) of fig. 5.3. Diagram (iii) illustrates the total salt content of the lagoon. During the 'bar closed' period this can be seen to very stable. Following the drop in rainfall and river run-off during the period immediately after bar opening, there was an overall increase in the salt content of the lagoon. As run-off gradually increased the salt content of the lagoon gradually decreased, probably reaching a minimum in October. Unfortunately no data is available for the period of maximum rainfall and run-off in mid-October. Data from previous years (Mandelli and Botello 1976) show that an average salt content as low as 1.0×10^5 tons (salinity $3^o/_{oo}$) may be encountered in Chautengo during high rainfall periods.

Consideration of the parameter 'total salt content' is often more useful than salinity for studying the exchange of

Figure 5.3

LAGUNA CHAUTENGO - THE

EFFECT OF EXTERNAL PHYSICAL FACTORS ON
PHYSICAL PROPERTIES OF THE LAGOON.



LAGUNA CHAUTENGO
THE EFFECT OF EXTERNAL PHYSICAL FACTORS ON PHYSICAL PROPERTIES OF THE LAGOON

dissolved substances with the sea, as it is not affected by simple evaporation and dilution. For the period when the lagoon is communicated with the sea the " % fresh water " (defined in diagram (v)) may be used to show the relative importances of the run-off and sea water sources controlling the mean salinity of the lagoon and is particularly useful to illustrate horizontal distribution within a lagoon (see later).

For the case of the Laguna Mitla, salinity values are difficult to interpret. This is because the conductivity - salinity relationship is not accurately defined at the low salinities involved ($2.5 - 4.0^{0}/_{00}$) and that the development of anoxic conditions may significantly alter the chemical composition of the water. From depth observations in the lagoon it was seen that it has an average depth of about 3 metres. Following the first rains in June there was only a very slight increase in the lagoon depth. This was probably due to the unusually low local rainfall, coupled with drainage through the Canal Carrizal. The second period of heavy rainfall in October, resulted in an increase in lagoon depth of about 1.5 metres. Blockage of the Canal Carrizal trapped much of this water in the lagoon for the remaining part of the survey period.

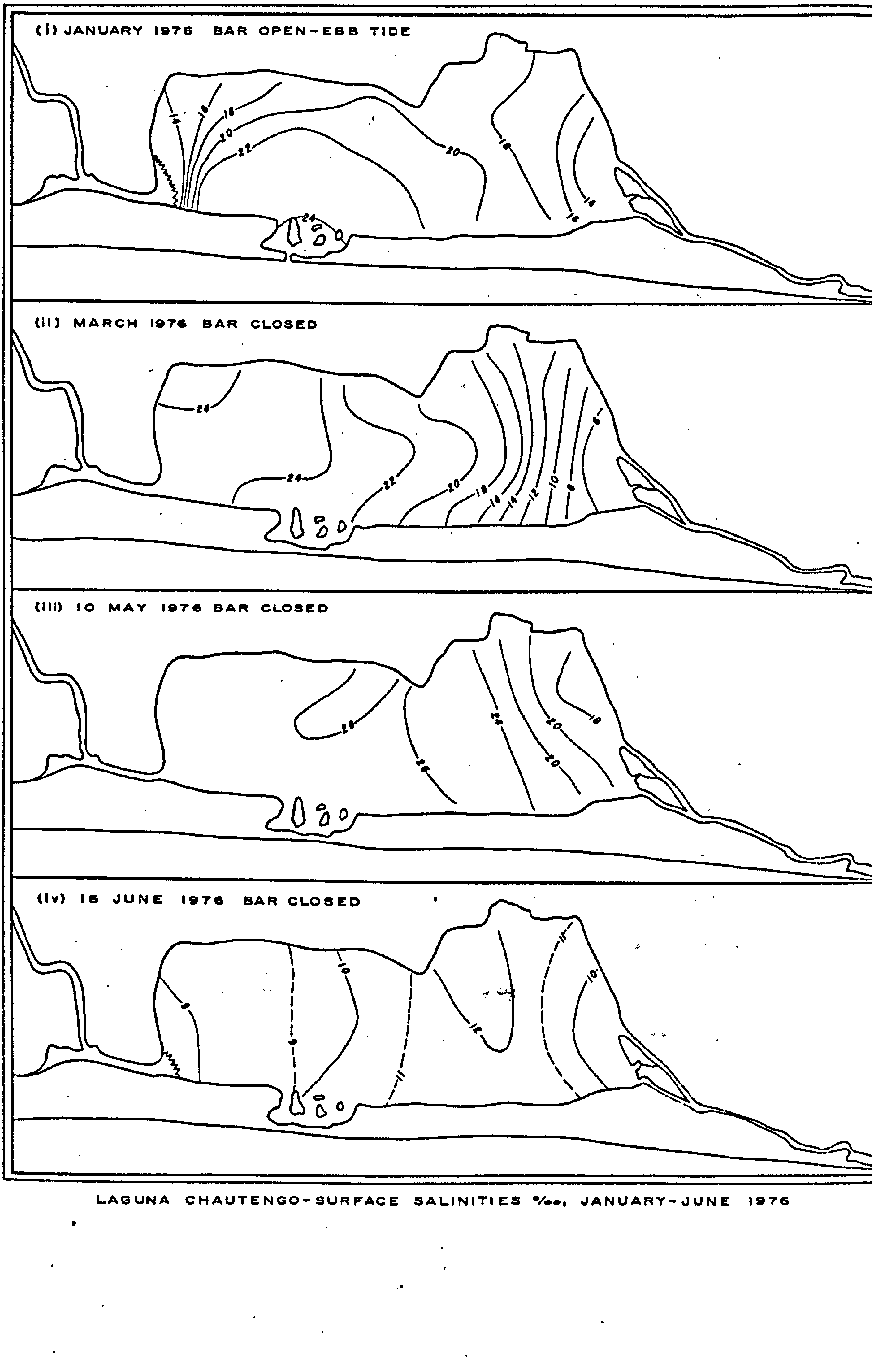
5.2 Circulation and Mixing

For the case of the Laguna Chautengo, the seasonal variations in the salinity distribution may be obtained from fig. 5.4. The figure shows the surface isohalines during the period from just before bar closure to just before bar opening. In the January survey, the river flow in the Rio Nexpa had

Figure 5.4

LAGUNA CHAUTENGO -
SURFACE SALINITIES ‰

JANUARY-JUNE 1976.



LAGUNA CHAUTENGO-SURFACE SALINITIES °/oo, JANUARY-JUNE 1976 decreased to ca 1.6m^3/sec. The diagram shows three basic areas :-

(i) A large, roughly semicircular area of salinity 20-24$^o/_{oo}$ radiating from the bar inlet.

(ii) A region of closely-packed isohalines near the discharge of the Rio Nexpa. These isohalines are more widely spaced toward the North, suggesting mixing in that direction.

(iii) An area of widely spaced isohalines of decreasing salinity toward the Rio Copala (at the East of the lagoon). Since the Rio Copala is smaller than the Rio Nexpa, this distribution tends to indicate a more stable salinity regime in the eastern basin of the lagoon.

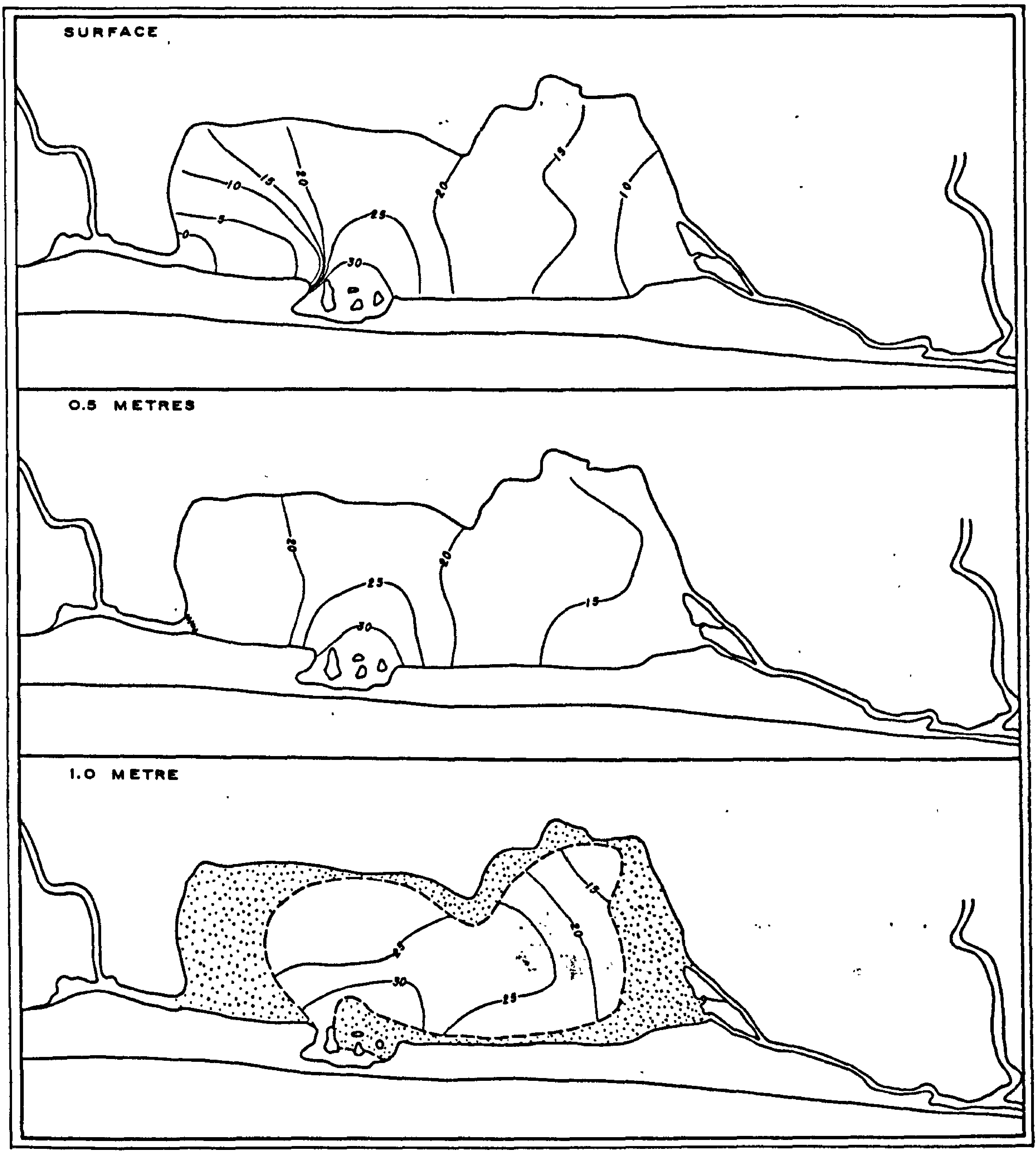
The March survey was about three weeks after bar closure. The high salinity (24.1$^o/_{oo}$) in the region of the Rio Nexpa discharge illustrates the very small flow of the river. The small flow of the Rio Copala however, maintained a large salinity gradient in the eastern basin of the lagoon. May conditions were very similar to those of March; wider spacing of the isohalines and the smaller salinity range reflect the effect of 3 months evaporation and the considerably reduced input of the Rio Copala.

The June survey followed the start of the rainy season as described earlier. The lagoon can be seen to have a very small salinity range (ca 8-12$^o/_{oo}$) and though there was a general decrease of salinity towards the two river discharges, there was no clear evidence of these as the original sources of the large water input.

Following the opening of the bar inlet in July, an

Figure 5.5

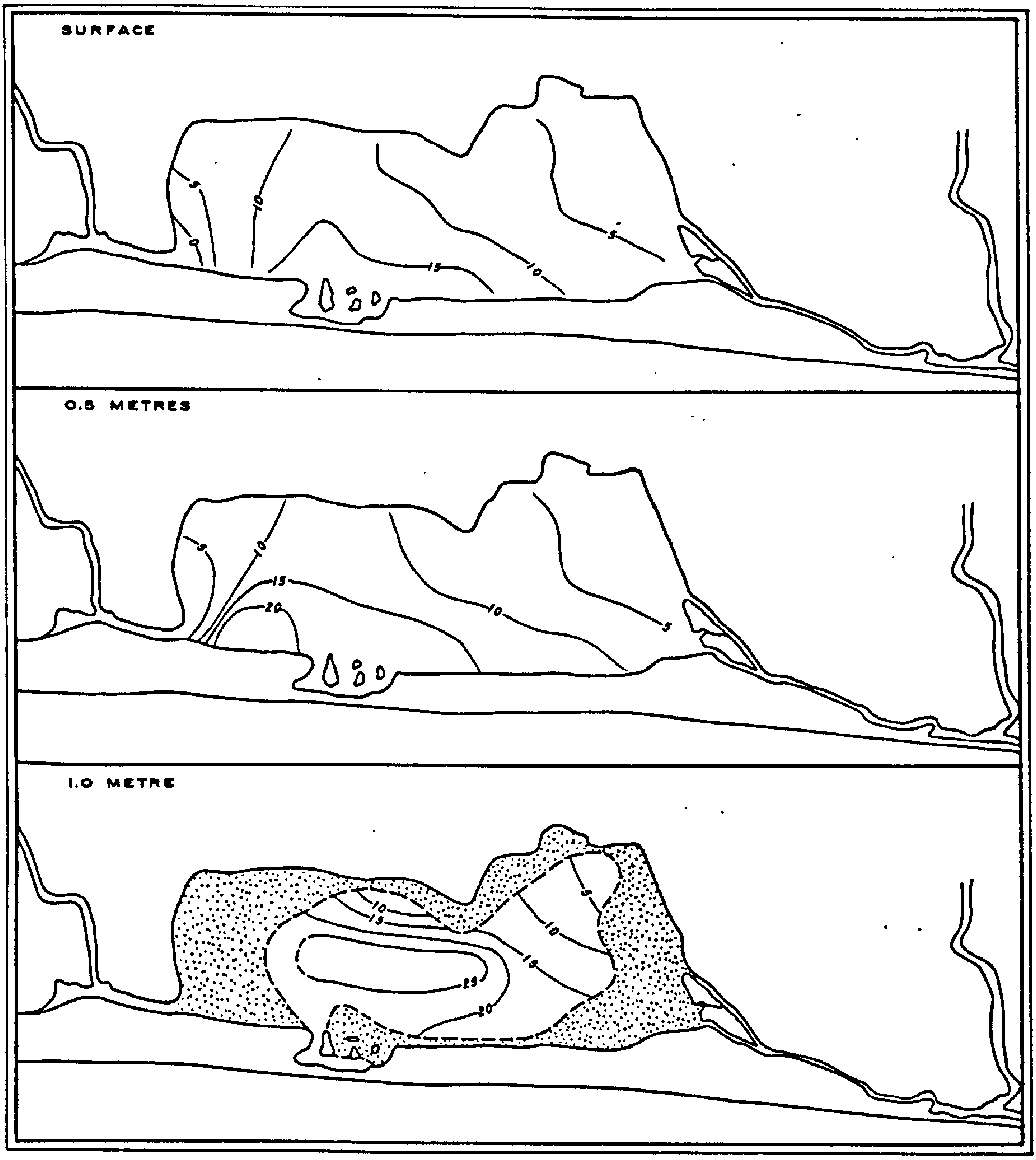
LAGUNA CHAUTENGO -
MORNING SURVEY, FLOODING TIDE,
18th JULY 1976 - SALINITIES (‰)



LAGUNA CHAUTENGO - MORNING SURVEY, FLOODING TIDE, 18 JULY 1976 - SALINITIES (‰)

Figure 5.6

LAGUNA CHAUTENGO -
AFTERNOON SURVEY, EBBING TIDE,
1st NOVEMBER 1976 - SALINITIES (‰)



LAGUNA CHAUTENGO-AFTERNOON SURVEY, EBBING TIDE, 1 NOVEMBER 1976-SALINITIES (‰)

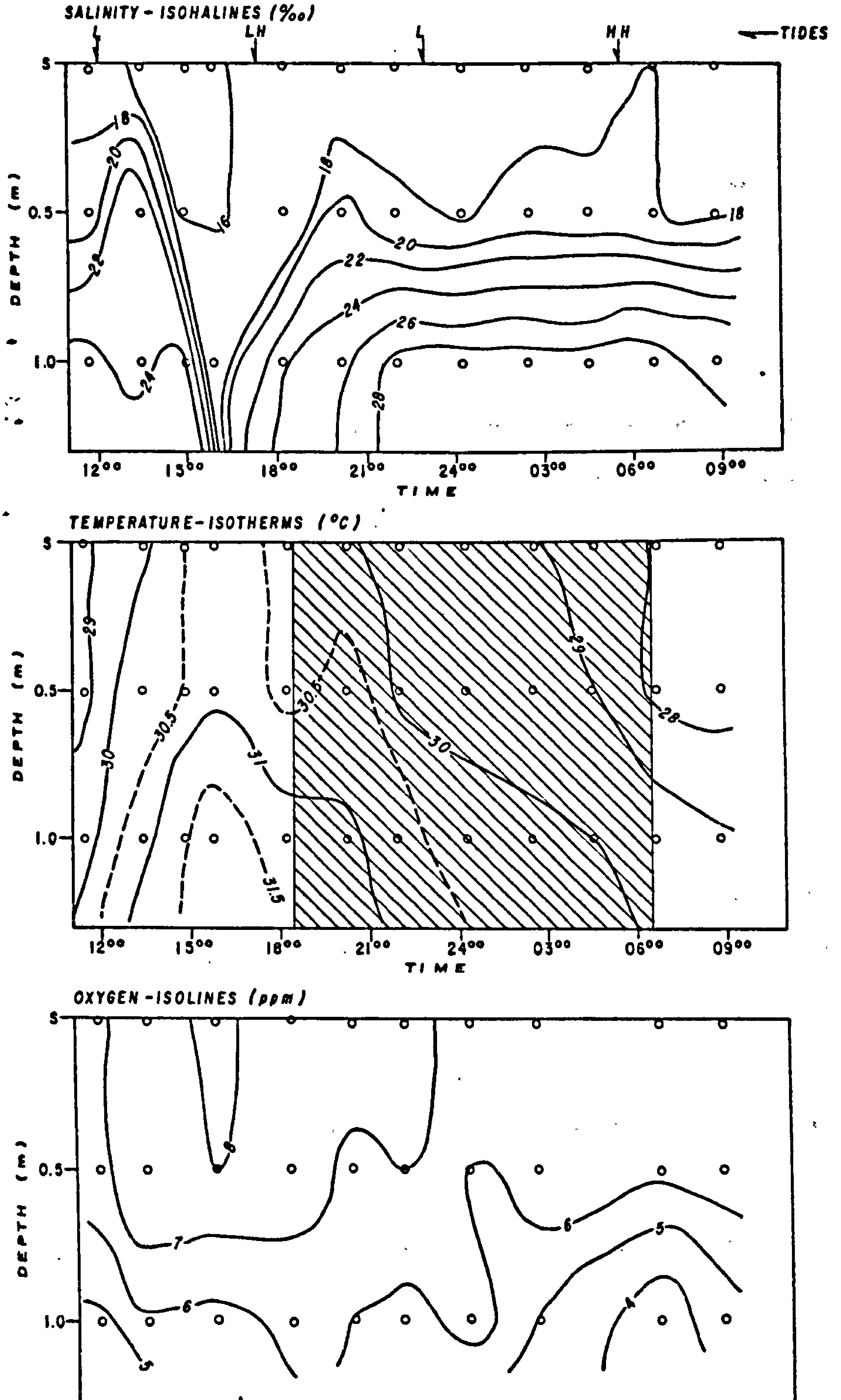
overall salinity distribution developed similar to that shown for January (fig. 5.4). This overall distribution was found throughout the 'bar open' period. However, the detailed distribution is interesting, as it shows the effect of stratification in the lagoon. Fig. ~~4~~5.5 shows the horizontal distribution of isohalines at three discrete depths, (surface, 0.5 metres, 1.0 metres) for a flooding tide in July 1976. The surface distribution shows the long plume of river water stretching towards the bar inlet. A 24 hour study at the inlet in September showed that this plume may extend through the inlet to the sea during the ebb tide. A second and smaller river plume may be seen extending from the discharge of the Rio Copala. The 0.5m distribution of isohalines may be seen to be entirely different. Both river plumes are absent and a smaller salinity range is encountered. The river water therefore, was spreading above this layer and its total depth never exceeded 35 cm. The distribution at 1.0m (where the lagoon was sufficiently deep) shows the effect of sea water entering the lagoon, sinking and mixing as it spreads inwards along the lagoon floor. The sharp salinity increase denoting this bottom layer was generally found at a depth of 80-100 cm.

A further example of the effect of stratification is given in Fig. 5.6 for an ebbing tide in November 1976. The same general features may be observed in these diagrams as those in Fig. 5.5 but the surface river plume is not strongly pronounced, despite the higher river flow in this period. This is probably a result of the November survey being conducted during the strong afternoon onshore breeze which tends to break up the thin surface water layer. The salinity distribution pattern for 1m depth illustrates particularly clearly, the manner in which higher salinity water spreads across the lagoon floor, extending into the two basins forming the lagoon.

The salinity distribution presented here, give little information as regards circulation in the lagoon. An experiment to observe tidal variations in a salinity profile at the bar inlet had to be abandoned owing to the high current velocity (up to 4 knots) and the presence of sharks. However, it was found that the inlet depth varied seasonally from 1 metre to ca 6 metres and considerable stratification was observed when the inlet was at its deepest both on the ebb and flood tides. When the river flow is sufficiently large it appears to be capable of suppressing the flood tide and leading to very low salinities in the lagoon. A 24 hour station, at station 3 in December is illustrated in Fig. 5.7. In the diagram, variations of salinity, temperature and oxygen are shown with respect to depth and time. The salinity plot shows the very strong stratification that existed in many areas of the lagoon, despite it being very shallow. From about 13.00 hours to 16.00 hours there was a steady increase in the depth to which the lower salinity water ($15.5 - 16.2^{o}/_{oo}$) penetrated. This effect does not appear to be due to mixing since mixing of the water column at 13.00 hours would produce a salinity of $22.7^{o}/_{oo}$ and not the $16.1^{o}/_{oo}$ found at 16.00 hours. A survey of the entire lagoon revealed that the only immediate source of this water would be from the area beyond the discharge of the rivers (Fig. 3.1). There are two possible effects causing this movement, tidal movements and wind action. The letters L, L.H, and HH on Fig. 5.7 indicate the times of Low Water, Lower High water and Higher high

Figure 5.7

LAGUNA CHAUTENGO - 24 HOUR STATION 10 DECEMBER 1976.



SALINITY - ISOHALINES (‰)

TEMPERATURE - ISOTHERMS (°C)

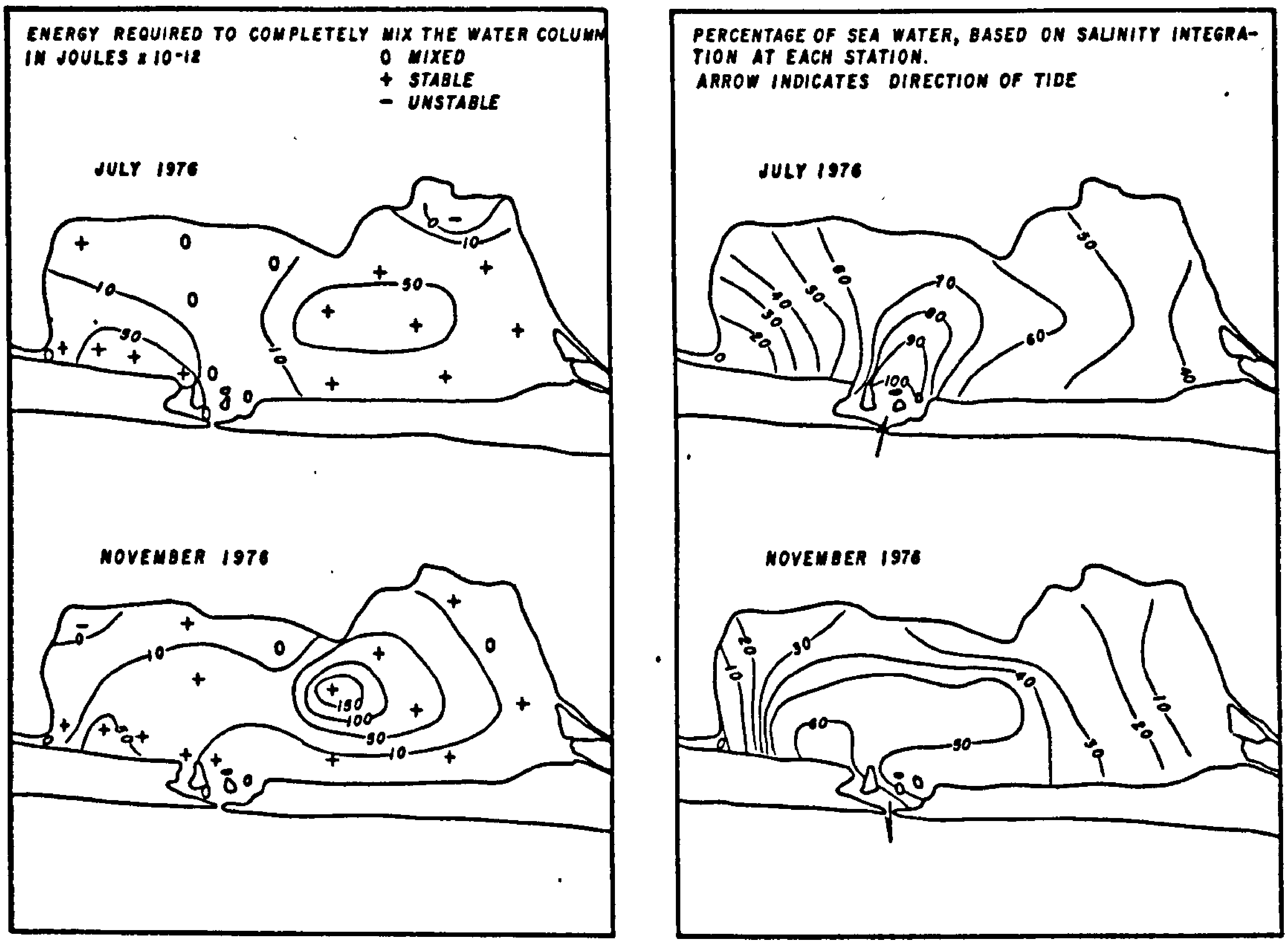
OXYGEN - ISOLINES (ppm)

LAGUNA CHAUTENGO-24 HOUR STATION, 10 DECEMBER 1976 water respectively. Since this postulated water movement occurs between low water and the lower high water, an even larger change would be expected between low water and the higher high water (23.00 hours to 0.5.30 hours); this however is not observed. The other possible effect is that of the wind. During the afternoon period (from 12.00 hours to 16.00 hours) a strong onshore breeze developed. The effects of this were particularly pronounced in the central part of the lagoon, where the absence of palm groves on the barrier allows the wind an uninterupted passage across the lagoon. A surface water movement was observed in the direction of the wind by observing the pathway of small aluminium foil floats but no quantitative experiments were conducted. It is suggested that a combination of both the effect of the wind and that of the incoming tide (suppressing the outflow of river water from the lagoon) may be responsible for these observations.

The temperature diagram in Fig. 5.7 gives little evidence as to circulation and mixing. Bottom temperatures were always higher than those of the surface layer. This effect may result from heating of the sediments and their subsequent back-radiation into the overlaying water or refraction of radiation, by the higher salinity lower water layer, reducing its back radiation into the surface layer. The effect was particularly pronounced during the afternoon period where the water was less highly stratified, suggesting a sediment influence in the temperature control of the water column. The oxygen diagram (Fig. 5.7) is similarly of little use in describing the general mixing and circulation since large diurnal oxygen changes are observed as a result of the processes of photosynthetic production and respiration.

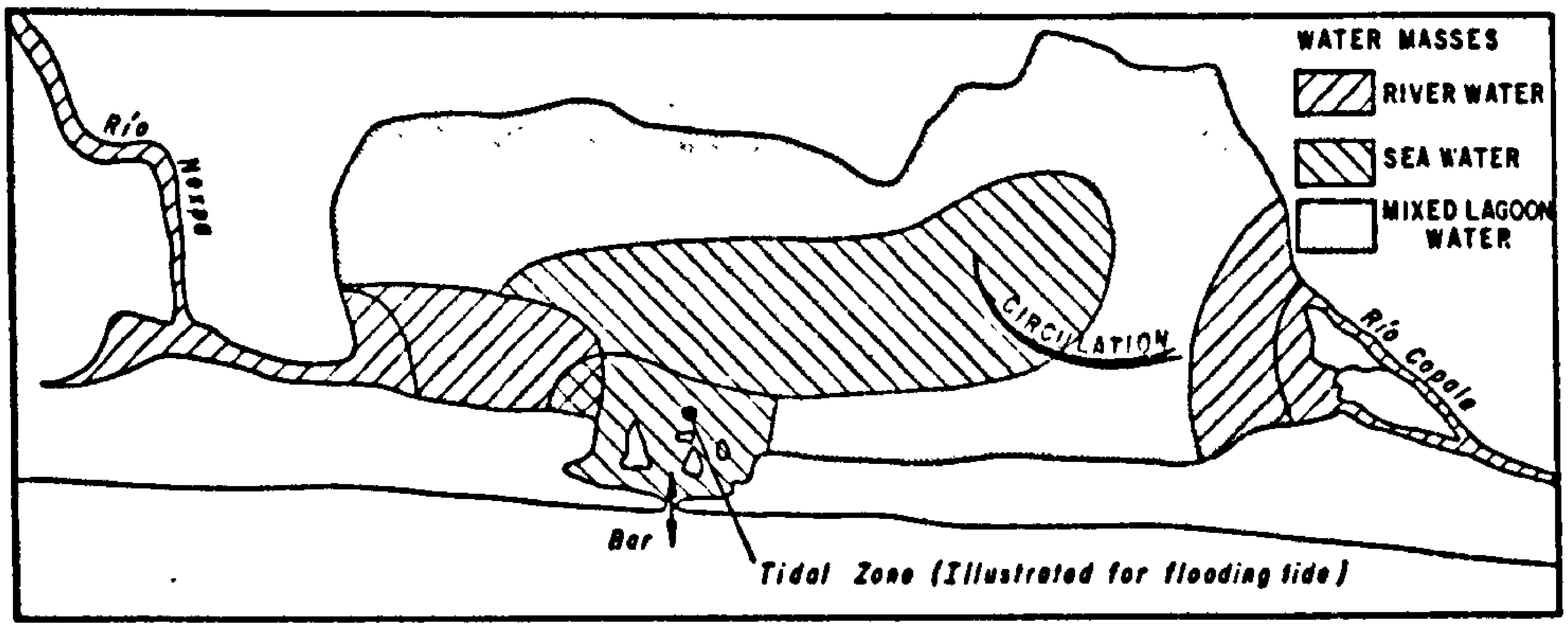
Figure 5.8

LAGUNA CHAUTENGO - CHARACTERISTICS CLASSIFYING DISTRIBUTION OF WATER MASSES



(I) DISTRIBUTION AND INTENSITY OF STRATIFICATION

(II) PROPORTION OF SOURCE WATER IN TOTAL COLUMN



(III) SCHEMATIC DIAGRAM OF TYPICAL WATER MASS DISTRIBUTION

LAGUNA CHAUTENGO–CHARACTERISTICS CLASSIFYING DISTRIBUTION OF WATER MASSES sea water than in the western basin, despite the larger flow of the Rio Nexpa than of the Rio Copala. This suggests a longer residence time of fresh water in the eastern basin of the lagoon. It is interesting to compare this finding with the very similar observations in Fig. 5.4, when the lagoon was isolated from the sea. It is possible that both observations are a result of a pattern of circulation which limits the exchange of water between the two halves of the lagoon.

In the final diagram (diagram (iii)) of fig. 5.8, a schematic diagram is presented of a typical water mass distribution in Chautengo. Three water masses are recognised: sea water (including partially diluted sea water, salinity 27-33$^{\circ}/_{oo}$); river water (including water salinity 0-5$^{\circ}/_{oo}$); and mixed lagoon water which is a mixture of the two source waters. Stratification is shown by superposition and a tidal zone is illustrated which, according to tidal state and bar morphology, may be occupied by sea water, mixed lagoon water or a stratified system including both. It must be stressed that the scheme presented in this diagram is only intended to give a very general impression of the water masses involved.

The mixing and circulation in the Laguna Apozahualco appears to much less complicated than for the case of Chautengo. No stratification was observed, except in a small 1.8 metre basin (Station 1) following the large run-off of water into the lagoon prior to bar opening. At this station, the following observations were made :-

Depth	Temp. °C	Salinity $^{o}/_{oo}$
Surface	31.8	14.7
0.5 m	33.8	28.5
1.2 m	40.5	95.0

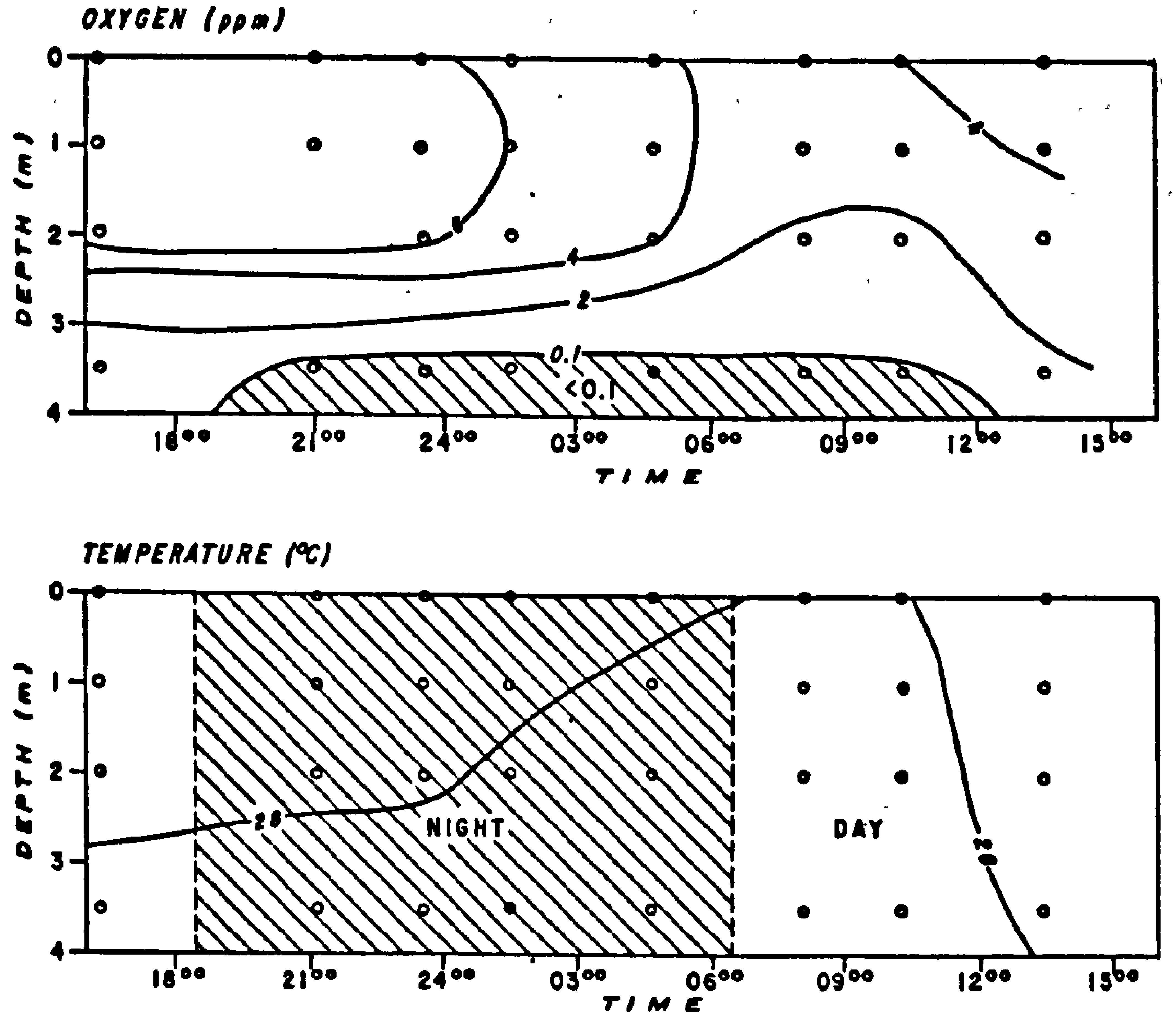
Though this small basin was of minimal importance to the overall water mass distribution in the Laguna Apozahualco, this effect may be very important for basins in other larger hypersaline systems. During the period of communication with the sea, salinity values for Stations in Apozahualco were generally within the range $25^{o}/_{oo}$ - $33.3^{o}/_{oo}$. This demonstrates the very limited run-off into the lagoon and the large influence of sea-water exchange on its resultant salinity.

The circulation and mixing pattern in the Laguna Mitla contrasts with the two previous examples. In Mitla, there is almost no marine influence and throughout most of the year, the salinity did not exceed $4^{o}/_{oo}$. However, stratification was observed and the mixing process played an important role in the chemistry and biology of the lagoon. Figure 5.9 shows diurnal variations with depth of temperature and oxygen during surveys in January and September at Mitla Station 3. In both surveys, there were homogeneous salinity conditions and hence temperature was probably the most important indication of water mass structure. The mean surface temperature for January (28.4°C) was lower than that for September (32.5°C), reflecting the air temperature variations (Fig. 4.3), and the temperature range in September

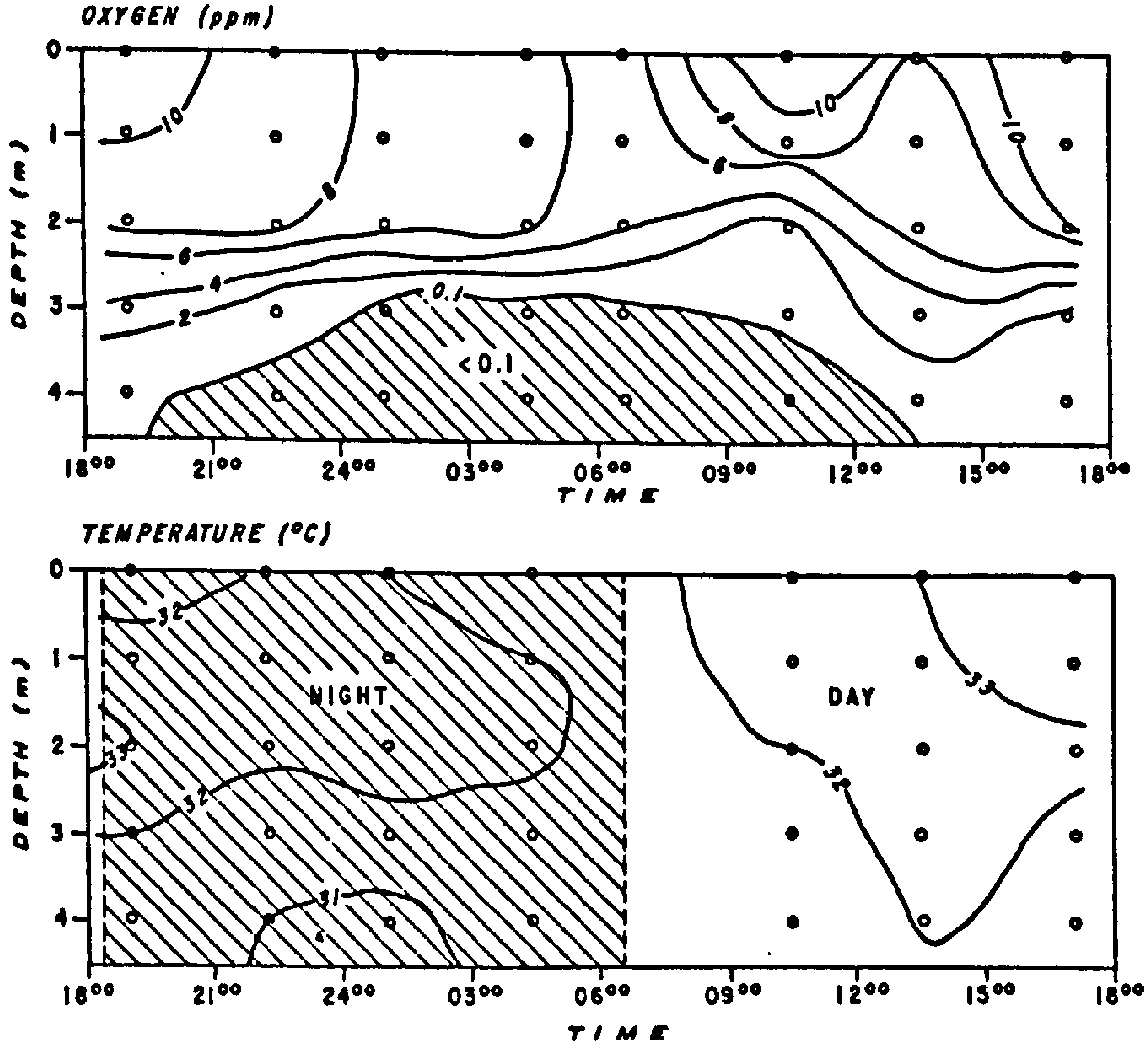
Figure 5.9

LAGUNA MITLA - WINTER AND SUMMER DIURNAL CHANGES

(i) 24 HOUR STATION - 19 JANUARY 1976



(ii) 24 HOUR STATION - 9 SEPTEMBER 1976



LAGUNA MITLA-WINTER AND SUMMER DIURNAL CHANGES was slightly larger (1 deg C January; 1.7 deg C September) than in the January survey. Similar overall conditions may be seen for the two surveys. Gradual cooling of the water column during the night gives a temperature minimum at dawn. Rapid surface heating occurs during the day and the heating process affects the entire water column by the middle of the day.

During the period from October through December 1976, the Laguna Mitla became completely stratified. This followed a large run-off into the lagoon during the intense rainfall experienced in mid-October. The lagoon stratified into two layers. The top layer, 3 metres deep was of salinity ca $3.1^{o}/_{oo}$ and the lower layer ca $14.4^{o}/_{oo}$. This effect, coupled with a temperature stratification, prevented the diurnal mixing described earlier. A gradual breakdown of this stratification occurred so that the diurnal mixing cycle was restored by the time of the February 1977 survey. These observations will be presented in greater detail in the next chapter.

6. Chemistry

6.1 Seasonal variations

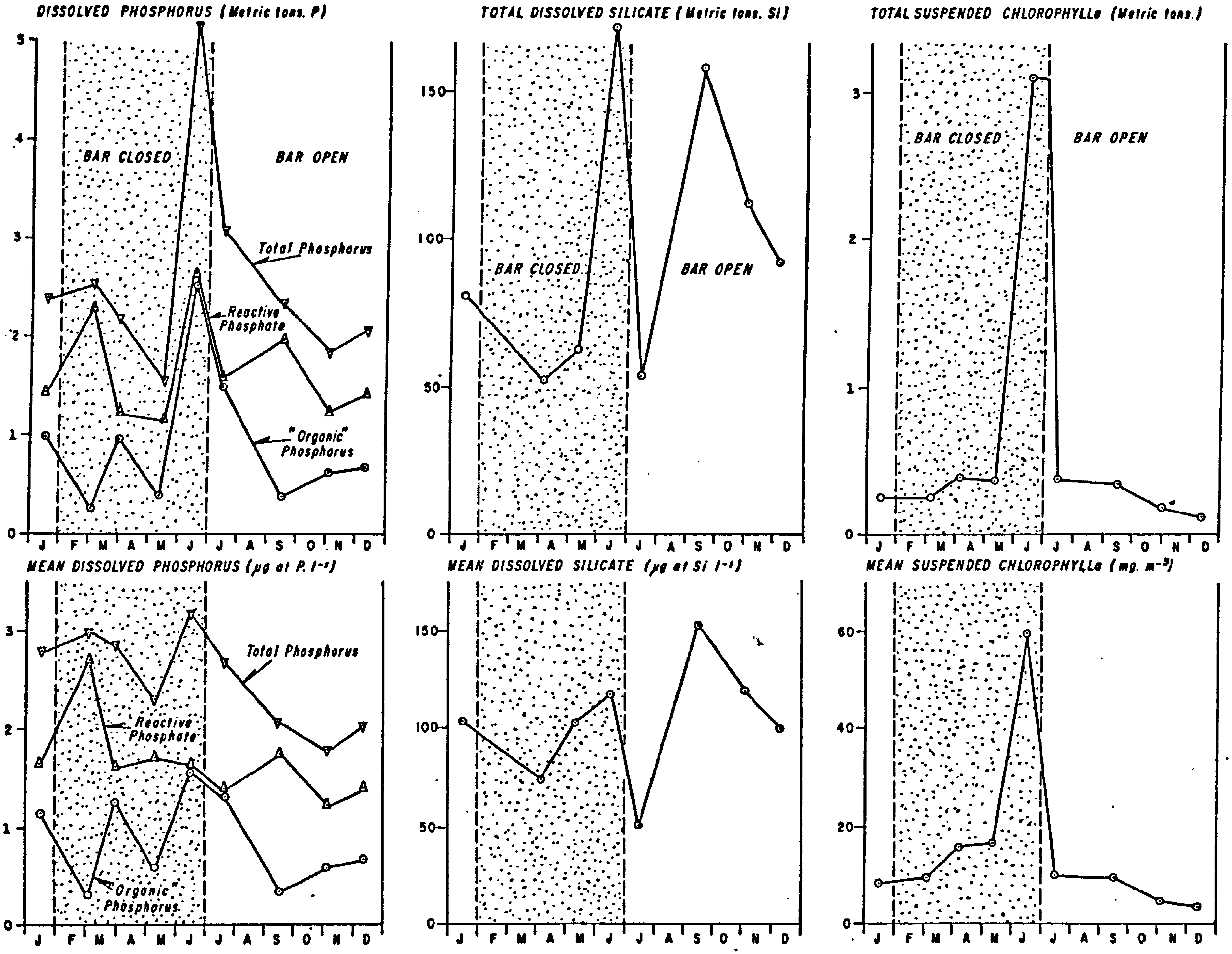
The pattern of seasonal variations in the Laguna Chautengo is presented in table 4.2. Fig. 6.1 illustrates the seasonal variations in phosphorus, silicate and chlorophyll$_a$. Results are expressed in terms of estimated total quantities of each constituent in the lagoon and of its concentration in the water. These two quantities do not always exhibit the same variations. For example, there is a large increase in the amount of reactive phosphate in the lagoon in June after the first rains increase its volume but the mean concentration of phosphate is slightly lower than for the previous month.

From fig. 6.1 it can be seen that during the dry season (January - May) there was an overall decrease with time in the total quantity of dissolved phosphorus and dissolved silicate present in the lagoon. During this period there was also an overall increase in the total suspended chlorophyll$_a$ in the lagoon. Insufficient data exists to show whether there is a direct relationship between the increase in the standing crop of primary producers (shown by chlorophyll$_a$) and the overall decrease in the dissolved nutrients presented.

The minimum total dissolved silicate was observed in April, corresponding with the maximum total suspended chlorophyll$_a$ for the 'bar closed' period. This observation is probably related to the silicate required to maintain the large diatom population of the lagoon, shown for the previous year to form ca 75% of the total phytoplankton population Licea _et al_ (1976). A slight

Figure 6.1

MONTHLY VARIATIONS IN DISSOLVED PHOSPHORUS AND SILICATE AND SUSPENDED CHLOROPHYLL $_a$



NTHLY VARIATIONS IN DISSOLVED PHOSPHORUS AND SILICATE, AND SUSPENDED CHLOROPHYLL increase in the total dissolved silicate in the lagoon between the April and May surveys may have resulted from silicate entering the lagoon by run-off or by re-solution of particulate silica following the death of diatoms. Using the average concentration (ca. 250 µg at Si 1^{-1}) found in the water from the higher reaches of the Rio Nexpa it would require an input of ca 1.3×10^6 m^3 of the water to produce the 10.43 ton (3.4×10^{11} µg at) increase in the silicate concentration observed. This is about three times higher than the river flow measured for this period (Secretaria de Recursos Hidraulicos) and as there was no other source of run-off into the lagoon this suggests a considerable contribution to the silicate supply from sources within the lagoon.

During the same period there was a steady decrease in the total dissolved phosphorus in the lagoon. This suggests a process involving continual loss of this constituent from the dissolved to the suspended particulate and sediment reservoirs. The decrease in the dissolved phosphorus concentration continued during the period April - May despite there being no change in the total standing crop of phytoplankton (expressed in terms of chlorophyll$_a$). Apart from a sharp increase at the time of the survey following bar closure, the mean concentration of reactive phosphate was very stable throughout this period and throughout the entire year of observations.

The large increase in the volume of the lagoon, following the first rainfall, was also marked by an increase in the total quantities of all the dissolved nutrients studied and by a heavy bloom of phytoplankton, the standing crop (as measured by chlorophyll$_a$) increasing to about eight times its May value. Following opening of the bar, discharge of the lagoon to sea level and exchange with the sea, the July survey showed that the chlorophyll$_a$ level had dropped to about its May level. This indicates a very large decrease in the standing crop of primary producers within the lagoon. Presumably much of the suspended particulate material was lost to the sea.

During the period when the lagoon communicated with the sea, there was a gradual decrease in the total dissolved phosphorus, the inorganic dissolved nitrogen and the suspended chlorophyll$_a$ within the lagoon. The dissolved silicate concentration rose to a maximum in September and then steadily decreased in the November and December surveys. A rough idea of the nutrient input to the lagoon may be obtained from table 6.1 where station 19 (river discharge) analyses are presented together with the river flow for the survey date.

Table 6.1 - Variation in the in-put of dissolved nutrients - Rio Nexpa.

Date	River flow m/sec	Silicate ug at Si l^{-1}	Total dissolved ug at P l^{-1}	Total Inorg. N ug at N l^{-1}
18 July	4.6	212.	4.18	18.1
11 Sept.	8.5	245.	2.60	-
1-2 Nov.	14.2	ca 260	2.93	2.2
9 Dec.	-	ca 300	2.54	2.0

This table shows a gradual decrease in the concentration of inorganic nitrogen nutrients in the river water, though it must be noted that organic nitrogen may be the main source of the element to the lagoon. A very slight decrease in the total dissolved phosphorus concentration is also noted but no decrease in the concentration of silicate was observed.

If the concentration of dissolved phosphorus and silicate nutrients at any station within the lagoon is a result of a mixture between the river and sea water sources of these materials, it should be possible to calculate the concentration of nutrients at any station, knowing the concentration of nutrients in the sea water and the river water and their salinities, together with the salinity at the station in question. This is attempted in table 6.2. The predicted and measured concentrations are shown for station 12, close to the Rio Nexpa; station 10 in the middle of the lagoon and for the overall mean of all stations in the lagoon. In the final column, the anomalies between the measured and predicted values are shown. These anomalies may result from :-

(i) Biological activity - the uptake and regeneration of nutrients.

(ii) Incorporation and release of nutrients to or from the sediments.

(iii) Short-term variations in the concentrations of nutrients in the river or sea (affecting the original assumption).

For the case of silicate the largest anomalies were found at station 10 and for the overall mean for the lagoon. Largest anomalies were generally negative and suggest losses within the lagoon, possibly related to the production of diatoms, though the period of high negative anomalies in November was not accompanied by an increased concentration of chlorophyll$_a$. However, the

Table 6.2 - Measured and predicted nutrient concentrations and their anomalies in the Laguna Chautengo

Survey	Measured Concentrations		Station 12			Station 10			Overall mean for Lagoon			Anomalies		
	River Water	Sea Water	% Fresh Water	Concentrations Predicted	Concentrations Measured	% Fresh Water	Concentrations Predicted	Concentrations Measured	% Fresh Water	Concentrations Predicted	Concentrations Measured	STA. 12	STA 10	Mean for Lagoon
					Silicate µg at Si l^{-1}									
July	212	10	56.5	124.	117	44	100.	52.0	45	101	51	-7	-48	-50
Sept	245	10	56.5	143	166	52.3	133.	143.0	53.5	136.	153	+ 23	+10	+17
Nov.	260	10	77.8	204	223	56.8	152	142.0	66	176	120	+ 19	-10	-56
Dec.	300	10	37	117.3	136	39.4	52.	80.0	41	129	100	+ 19	+28	-29
					Total dissolved phosphorus µg at P l^{-1}									
July	4.18	1.3	56.5	2.93	3.82	44	2.70	3.04	45	2.60	2.69	+0.9	+0.3	+0.1
Sept.	2.6	1.3	56.5	2.03	2.37	52.3	1.98	2.28	53.5	2.00	2.06	+0.3	+0.3	+0.1
Nov.	2.93	1.3	77.8	2.56	2.60	56.8	2.48	2.14	66	2.38	1.77	0.0	-0.3	-0.61
Dec.	2.54	1.3	37	1.76	3.97	39.4	1.80	2.03	41	1.81	2.02	+2.2	+0.2	+0.21

large flow rate of the Rio Nexpa during this period (table 6.1) may have resulted in a faster rate of loss of suspended chlorophyll$_a$ to the sea, thus reducing the effect of any bloom. A further possibility (affecting the "whole lagoon" estimate) is that the Rio Copala discharge has a lower silicate concentration than that of the Rio Nexpa, thus resulting in an over-estimation of the silicate input to the system and a consequent over-estimation of the magnitude of the anomalies.

The observations for total dissolved phosphorus anomalies do not parallel those for silicates, the only negative anomalies occurring at station 10 and for the mean value in November. The general occurrence of positive anomalies may reflect processes of nutrient release from detrital material transported into the lagoon by run-off.

In summary, the seasonal variations in dissolved nutrients and suspended chlorophyll$_a$ in Chautengo follow the annual hydrographic cycle dissolved earlier :-

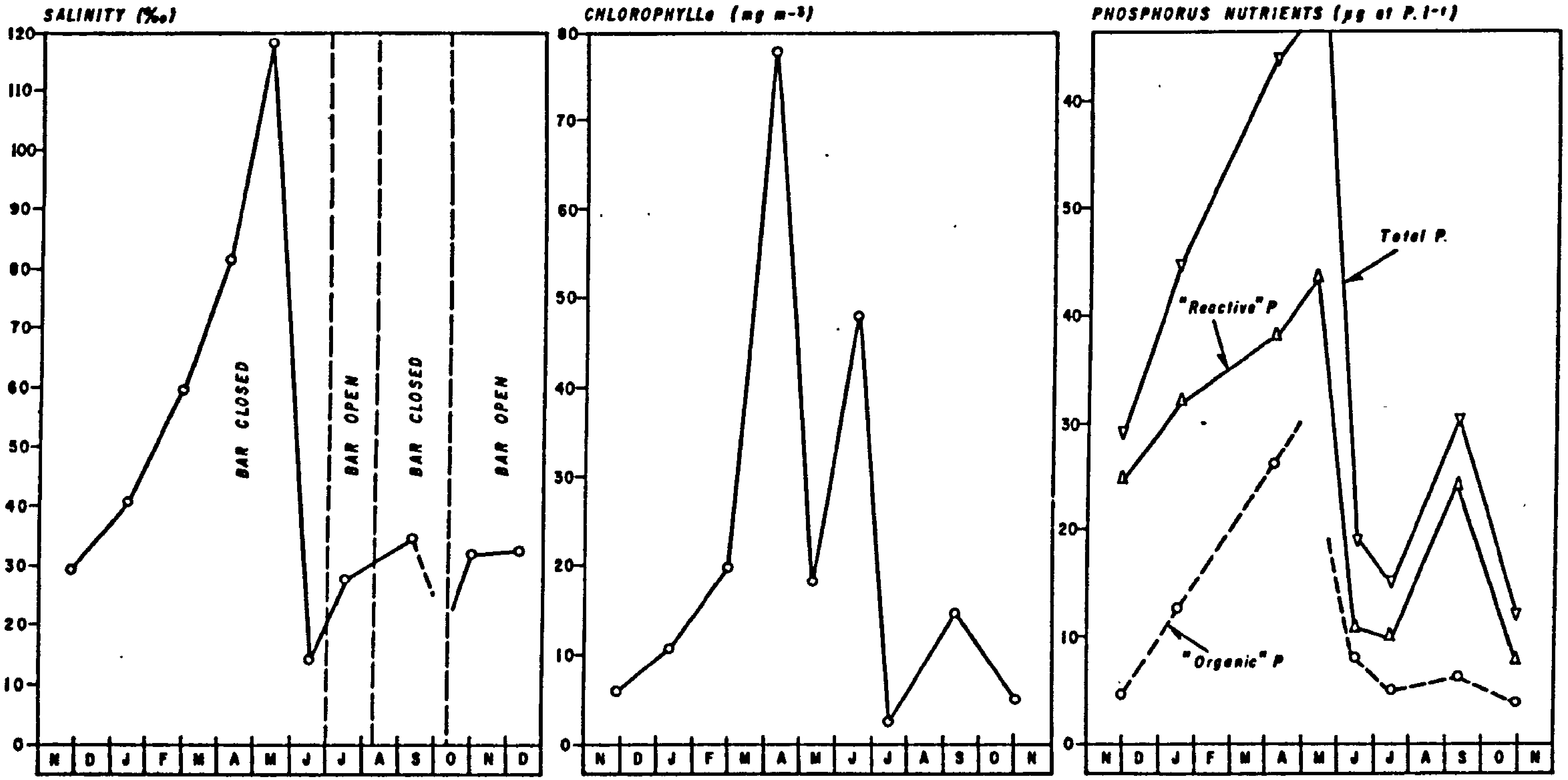
Stage I (Dry season, lagoon isolated) : There is a general decrease in the concentration of dissolved nutrients accompanied by a gradual increase in the suspended chlorophyll$_a$.

Stage II (Start of rainy season, lagoon fills): There is a large increase in the total quantity of dissolved nutrients and suspended chlorophyll$_a$.

Stage III (Bar opens, discharge to sea). Discharge of dissolved and suspended particulate material to the sea.

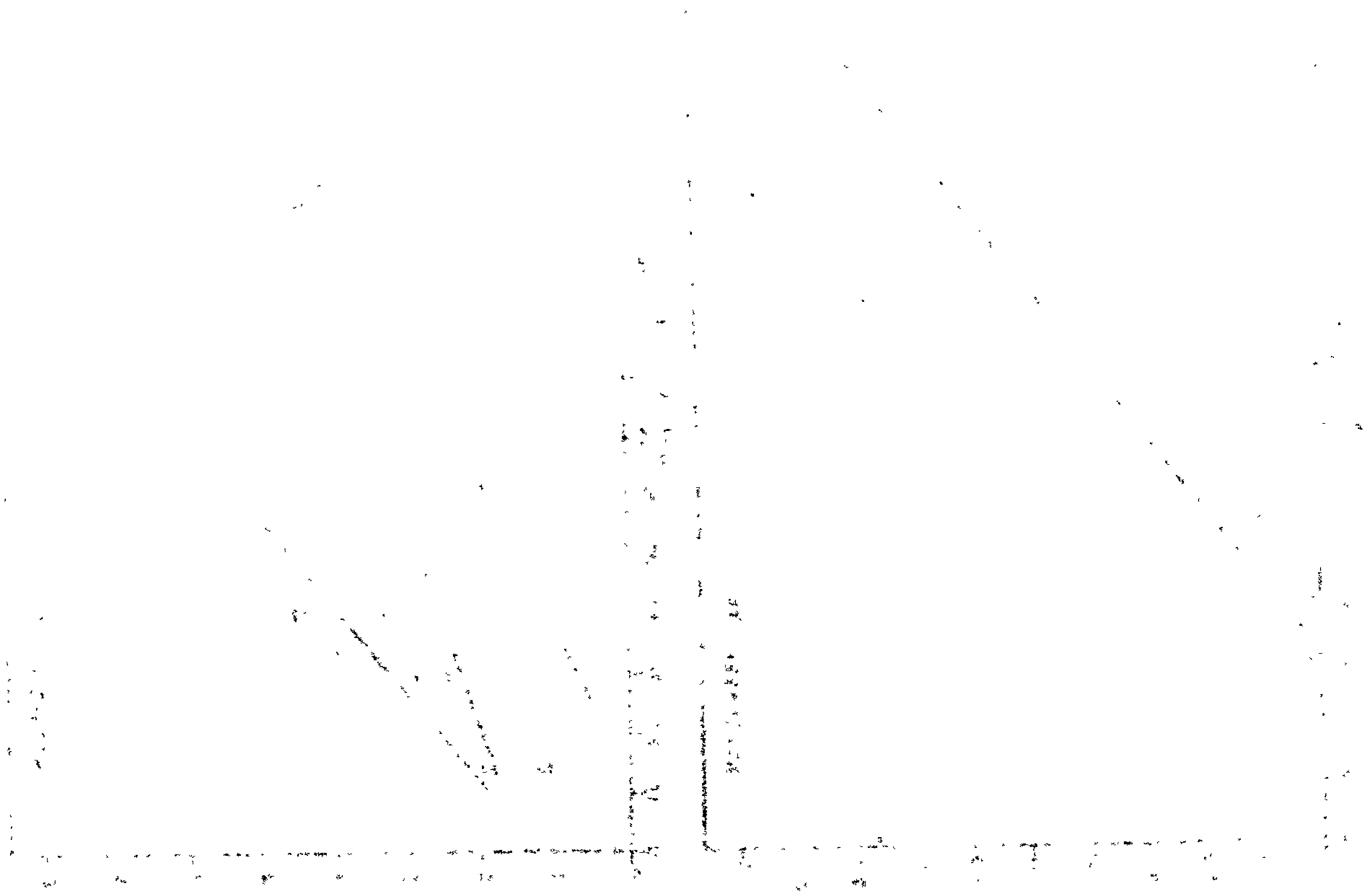
Stage IV (River run-off into the lagoon and tidal exchange with the sea). The concentration of dissolved nutrients in the lagoon is controlled by the mixing of river water and sea water together with the processes of uptake and

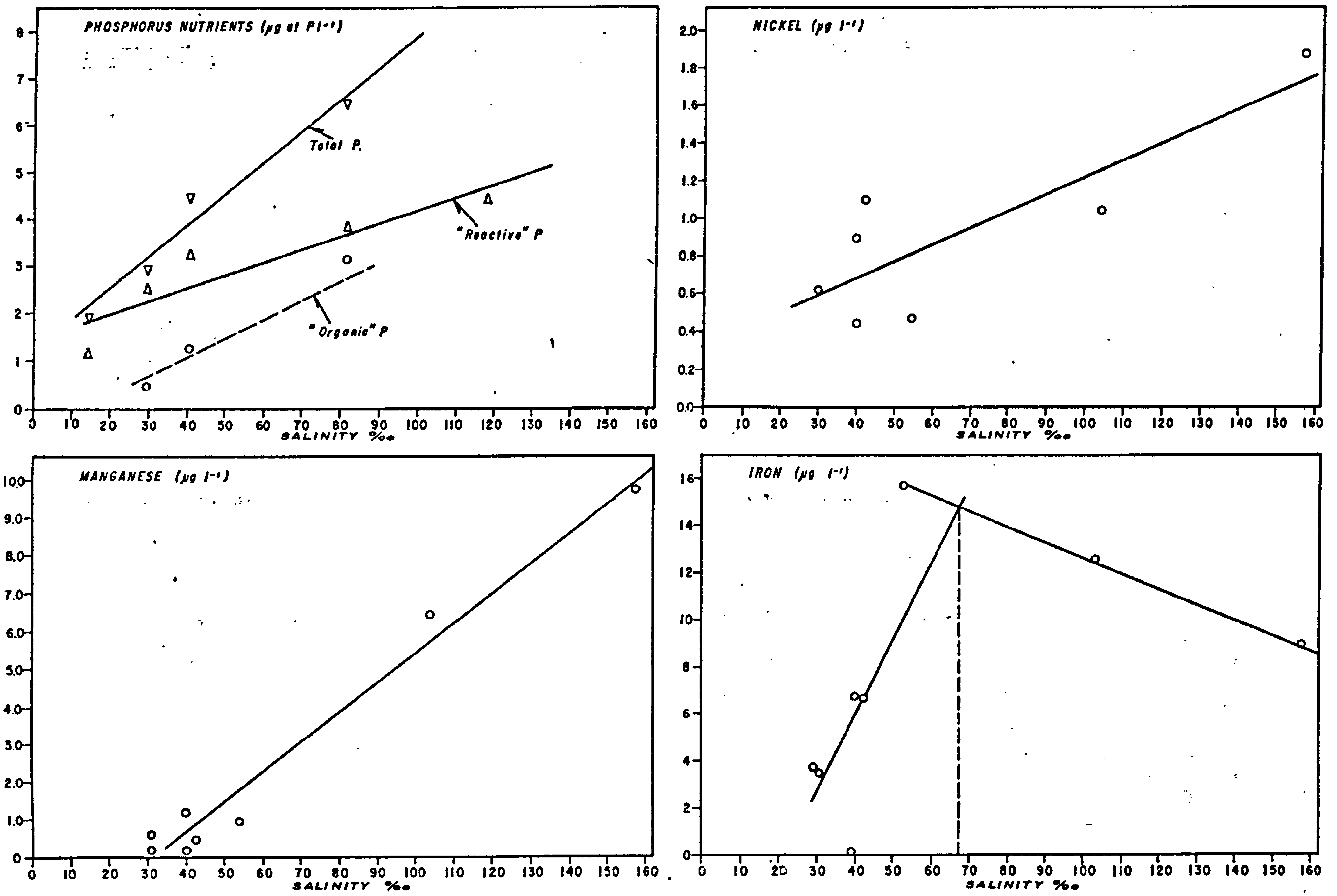
Figure 6.2
LAGUNA APOZAHUALCO . GENERAL SEASONAL CHANGES



LAGUNA APOZAHUALCO–GENERAL SEASONAL CHANGES

Figure 6.3
LAGUNA APOZAHUALCO
CONCENTRATION OF VARIOUS CHEMICAL
PARAMETERS DURING EVAPORATION.





LAGUNA APOZAHUALCO—CONCENTRATION OF VARIOUS CHEMICAL PARAMETERS DURING EVAPORATION the confidence level quoted and for the range of salinities observed there appears to be a linear relation between salinity and concentration for each of the parameters presented except for dissolved iron. The dissolved iron concentration increased with salinity up to a salinity of ca $68^{\circ}/_{oo}$. Beyond this point there was a steady decrease in the concentration of dissolved iron with salinity. The point of inflexion occurs at about the salinity ($70^{\circ}/_{oo}$) at which the iron should precipitate as Fe_2O_3 (Copeland 1967).

The examples investigated did not exhibit 'best fit' lines passing through the origin (the effect of doubling the salinity was not to double the concentration of the other parameter). This suggests that the concentration of each parameter, at lower salinities, is controlled by other effects such as biological and chemical equilibria with their particulate (organic and inorganic) reservoirs.

Following the start of the rainy season, the lagoon rapidly filled, the algal mat dispersed and there was a bloom of phytoplankton. The dissolved phosphorus concentration decreased but this did not reflect the total quantity of dissolved phosphorus in the lagoon since there had been a large increase in the lagoon volume. Unfortunately it is not possible to calculate this increase in volume from change in depth since the lagoon area also changed. The salinity change from May to June suggests about a nine fold increase in volume. Using this figure and the data in fig. 6.2 it can be seen that there was a net increase in the total reactive phosphate in the lagoon (ca 2 x) and that the total suspended chlorophylla in the lagoon was probably greater in June than in the April bloom of phytoplankton.

The flushing of the lagoon by the sea following the opening of the bar resulted in the high salinity (28$^{o}/_{oo}$) measured in the July survey. This was accompanied by a low total dissolved phosphorus concentration and a very low suspended chlorophyll$_a$ level. Following re-closure of the bar, there was a large increase in the reactive phosphate concentration. This effect had also been observed in the February survey of Chautengo (fig. 6.1) also following bar closure and may be a result of run-off after bar closure or the regeneration of phosphate from particulate organic material. During the bar-closed period there was also an increase in the concentration of suspended chlorophyll$_a$, again suggesting the in-put of dissolved nutrients by run-off or regeneration.

The final stage of the lagoon cycle was the re-opening of the bar and a further period of flushing as described for the July survey. The bar inlet finally closed in late December.

6.2 Eutrophication

The data for these lagoons illustrates various aspects of the process of eutrophication in tropical coastal lagoons. This section will consider the spatial distribution of nutrients and chlorophylla the seasonal and diurnal variations in productivity and detailed diurnal variations of chemical parameters.

6.2.1 The distribution of chemical parameters

The most detailed study of the distribution of nutrients and chlorophyll$_a$ was conducted in the Laguna Chautengo. Distribution will be shown by isoline diagrams; station positions and numbers are those shown in fig. 3.1.

For the dry season, an example of the distribution of salinity, silicate, suspended chlorophylla, and total dissolved phosphorus is given by fig. 6.4 (April survey). This survey was made after the bar had been closed for about two months. The salinity in the eastern basin of the lagoon was lower than in the western basin.

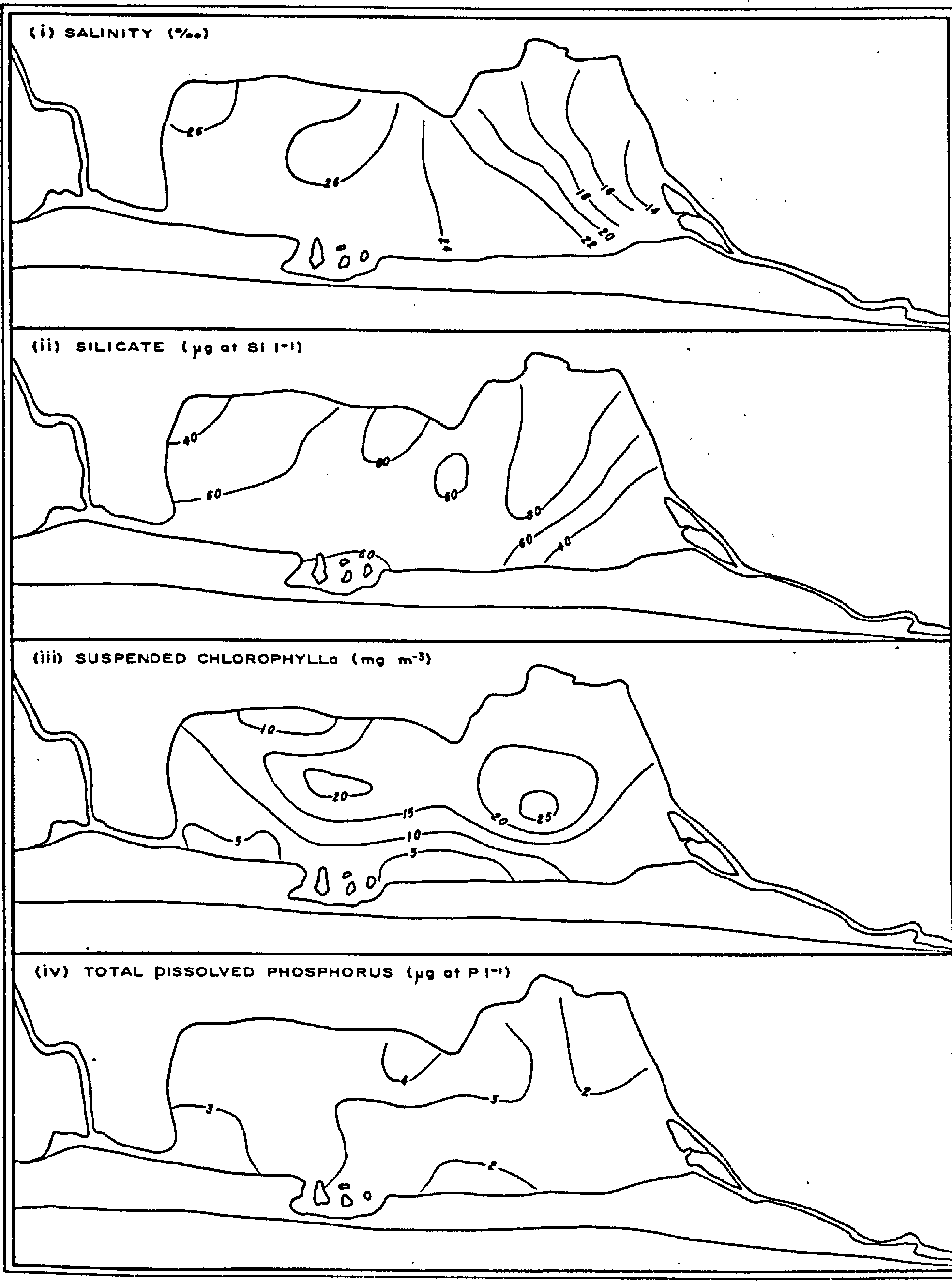
The highest chlorophyll$_a$ levels were observed in the central part of the two basins, the highest level being at station 5 in the deepest part of the lagoon. Chlorophyll$_a$ levels below 10 mg/m^3 were observed in the south-western part of the lagoon, the lowest values being found adjacent to the lagoon barrier.

Silicate showed a patchy distribution with the lowest values at the N.W. and S.E. extremes of the lagoon. There appears to be no simple correlation of these results with either the salinity distribution or the suspended chlorophyll$_a$ distribution. Total dissolved phosphorus similarly shows little correlation with any of the other parameters. Values presented were slightly higher in the western basin than in the eastern basin of the lagoon, possibly reflecting the higher phosphorus demand of the larger standing crop of phytoplankton in the eastern basin, but the data is not conclusive.

The main conclusion from this survey is that the highest chlorophyll$_a$ levels are associated with the deeper water areas and that the distribution of what are assumed to be the non-limiting nutrients, is patchy.

The distribution of nutrients for the June survey, at a time when the lagoon had been refilled (following the start of the rainy season) but in which the bar was still closed, is illustrated

Figure 6.4
LAGUNA CHAUTENGO
GENERAL CHEMICAL PARAMETERS
APRIL 1976



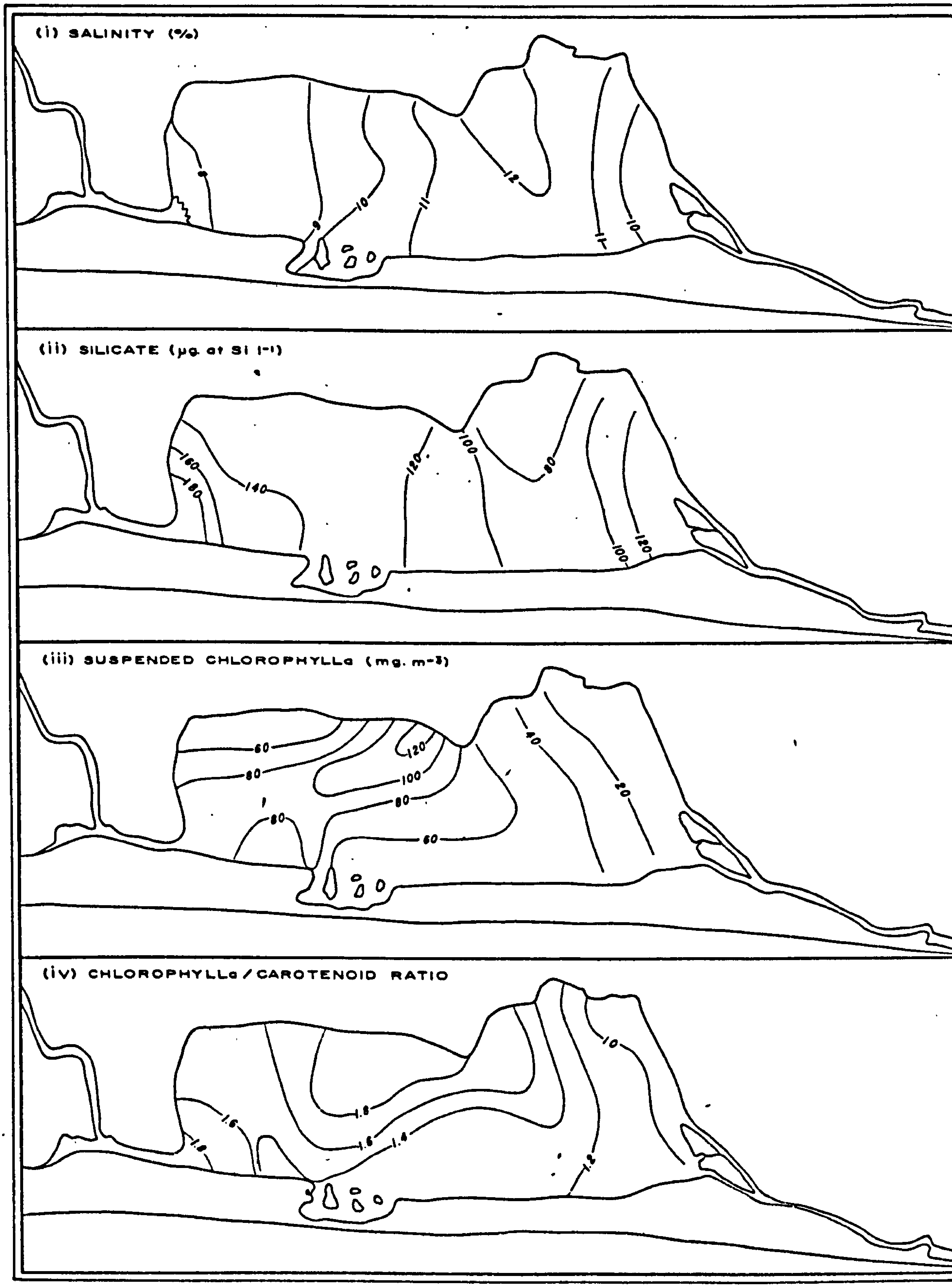
LAGUNA CHAUTENGO-GENERAL CHEMICAL PARAMETERS APRIL 1976 in figs. 6.5 and 6.6. The salinity distribution has been discussed in Chapter 5.

The silicate distribution can be seen to be opposite to that of salinity. The highest silicate concentration was observed off the discharge of the Rio Nexpa and a concentration gradient may be seen extending to the lowest values in the middle of the eastern basin of the lagoon. A second in-put may be observed from the Rio Copala.

The distribution of suspended chlorophyll_a did not relate to that of dissolved silicate. The highest values (100-121 mg/m^3) were observed extending in a plume from the northern bank of the lagoon. Lowest values were in the eastern extreme of the lagoon and the eastern basin of the lagoon in general exhibited much lower chlorophyll_a levels than the western basin. From the diagram it would appear that area of the most intense phytoplankton bloom is not directly associated with the discharge of the two rivers. However, the possibility arises that the bloom does not occur directly following river discharge since the water movement from the river flow could carry the standing crop away from the discharge area.

This possibility may be tested by examination of the state of development of the bloom at the data points. This may be achieved by the type of relation suggested by Margalef (1968) where a chlorophyll_a/carotenoid ratio is established. In a given bloom, high values of this ratio indicate the most recently produced organisms. This relation is illustrated in fig. 6.5 (iv) for the survey under consideration. It can be seen from this diagram that the areas of highest production of new organisms are in a plume off the north bank of the lagoon and in a smaller plume from the Rio

Figure 6.5
LAGUNA CHAUTENGO
GENERAL CHEMICAL PARAMETER
JUNE 1976


(i) SALINITY (‰)

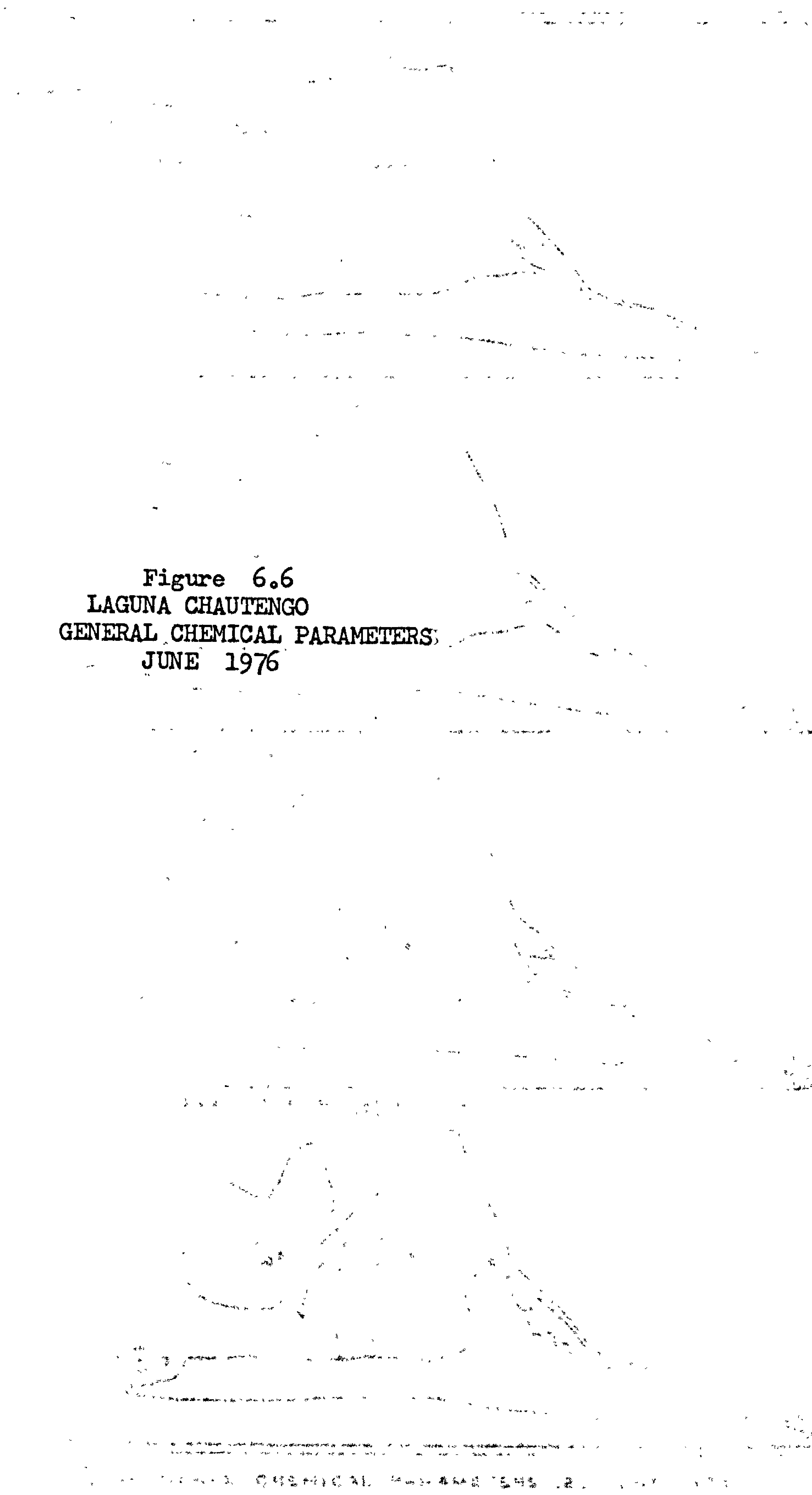
(ii) SILICATE (µg at Si l^{-1})

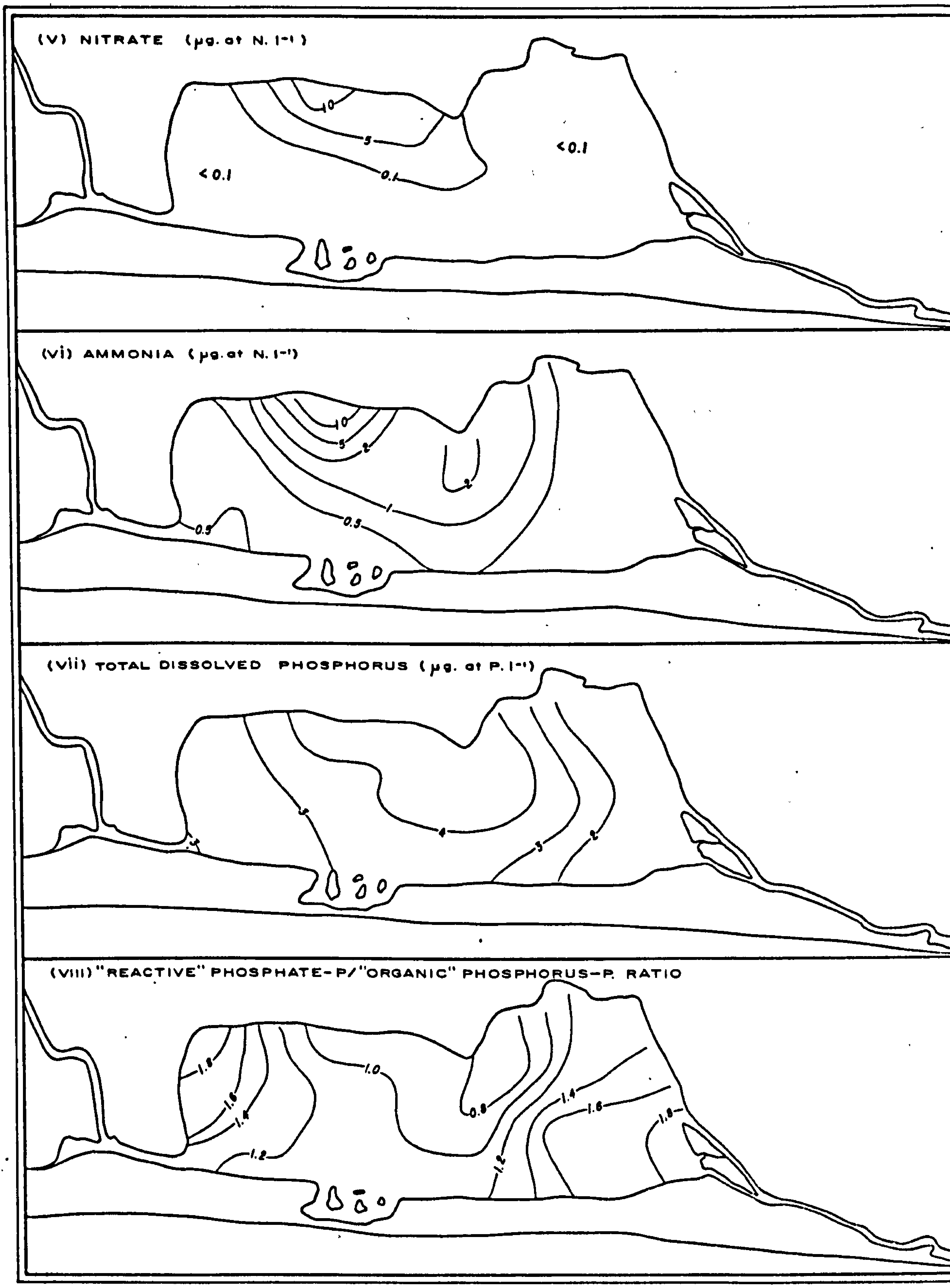
(iii) SUSPENDED CHLOROPHYLLa (mg. m^{-3})

(iv) CHLOROPHYLLa / CAROTENOID RATIO

LAGUNA CHAUTENGO-GENERAL CHEMICAL PARAMETERS (I) JUNE 1976

Figure 6.6
LAGUNA CHAUTENGO
GENERAL CHEMICAL PARAMETERS
JUNE 1976




(V) NITRATE (μg. at N. l^{-1})

(Vi) AMMONIA (μg. at N. l^{-1})

(Vii) TOTAL DISSOLVED PHOSPHORUS (μg. at P. l^{-1})

(Viii) "REACTIVE" PHOSPHATE-P/"ORGANIC" PHOSPHORUS-P. RATIO

LAGUNA CHAUTENGO-GENERAL CHEMICAL PARAMETERS (2) JUNE 1976

Nexpa. This suggests that there should be a nutrient source from the north bank of the lagoon. This nutrient source is confirmed by fig. 6.6 where plumes of nitrate, ammonia and total dissolved phosphorus may be observed centred on the area of discharge of a small seasonal stream which drains the area immediately to the north of the lagoon (see fig. 5.2).

At the time of the survey, there was extensive flooding to the north of the lagoon and it is suggested that run-off from this flood zone provided the principal source of phosphorus and nitrogen nutrients to the lagoon. This observation is also supported by the hydrographic study in Chapter 5 where it was found that the major input of water into the lagoon in the period before the June survey was from run-off from the immediate area surrounding the lagoon and not from the two major rivers.

The final diagram of fig. 6.6 shows the variations in the ratio between the reactive and organic forms of phosphorus. From the diagram it can be seen that the area with the highest proportion of organic phosphorus is that close to the northern bank of the lagoon. This may result from a high proportion of organic phosphorus in the original run-off or from high excretion by secondary producers. Areas with the highest proportion of reactive phosphate are in the N.W. and S.E. extremes of the lagoon, away from the main run-off.

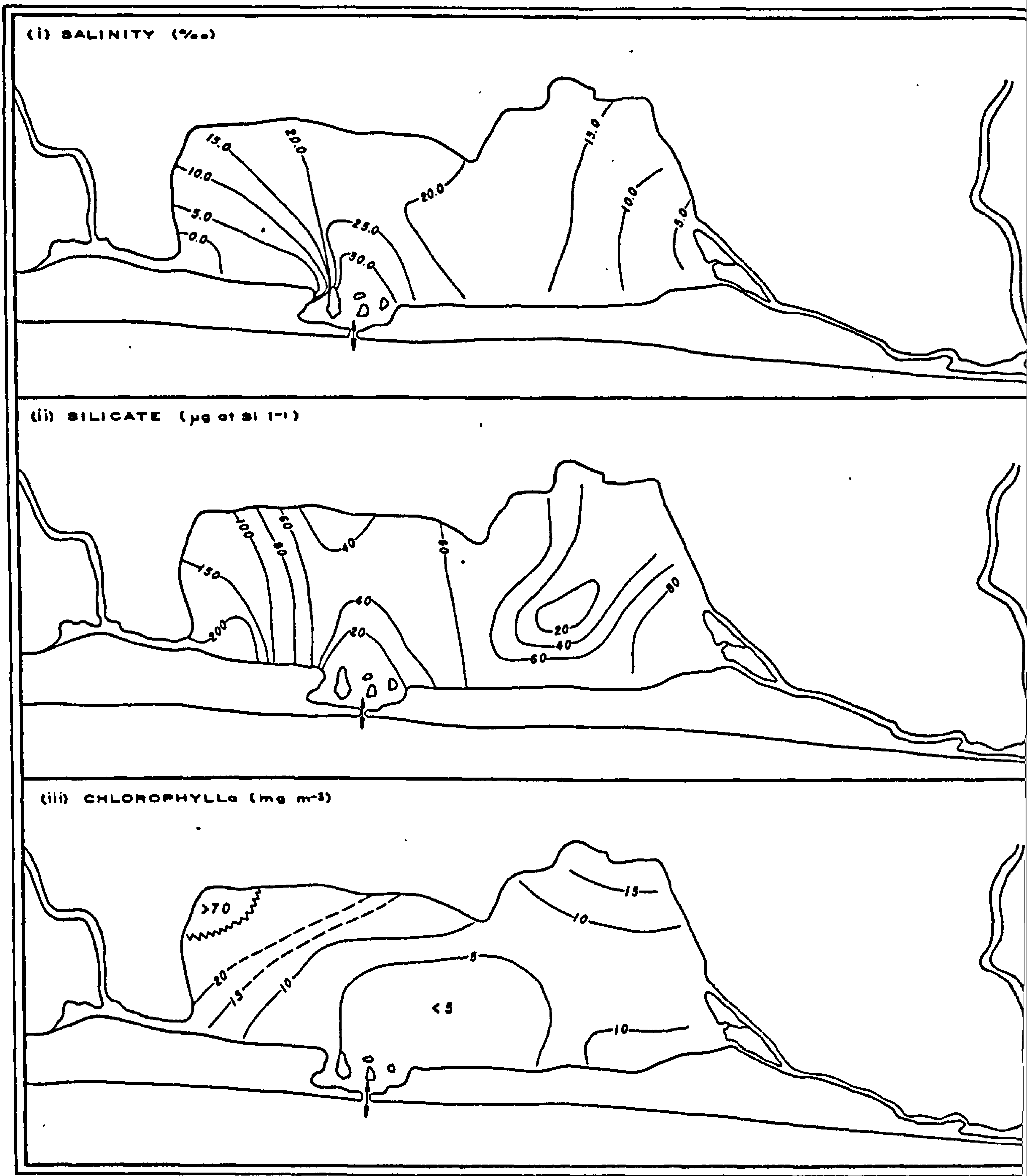
The third example of distribution of chemical parameters is taken from the July survey, when the lagoon had communication with the sea and received a significant river run-off. The survey was made on a flooding tide and at a time of low local rainfall and hence lower local run-off than that observed in the June survey.

From fig. 6.7 a similar pattern may be seen for the distribution of silicate and salinity in the western part of the lagoon. A plume of high silicate river water extends towards the bar inlet. The river water reaching station 14 from station 19 has undergone 6% mixing with sea water. The silicate concentration for the same water is however reduced to ca. 40% of its value at station 19. This suggests rapid uptake by diatom bloom off the river mouth. An area of low silicate concentration is also observed in the eastern basin of the lagoon, off the Rio Copala discharge again possibly due to uptake. These areas of uptake probably result in the silicate anomalies shown on table 6.2 and discussed earlier.

The chlorophyll$_a$ distribution in the survey shows the effect of the sea water exchange in the lagoon. A large area of low chlorophyll$_a$ may be seen extending towards the eastern basin of the lagoon from the bar inlet. An isolated patch of very high chlorophyll$_a$ was found at station 12 in the extreme N.W. of the lagoon, probably reflecting some northwards mixing of the water from the Rio Nexpa (see table 6.2). In all areas the chlorophyll$_a$ increased with distance away from the bar inlet.

Dissolved nutrient distribution is shown on fig. 6.8. The dissolved nitrate levels were generally below the minimum concentration for detection, as in almost all of the surveys conducted. The effect of the two rivers may be seen however, by the presence of two distant plumes, a strong plume from the Rio Nexpa discharge and a weaker plume for that of the Rio Copala. A similar picture emerges for the ammonia distribution.

Figure 6.7
LAGUNA CHAUTENGO
GENERAL CHEMICAL PARAMETERS
JULY 1976
(Surface)


(i) SALINITY (‰)

(ii) SILICATE (µg at Si l^{-1})

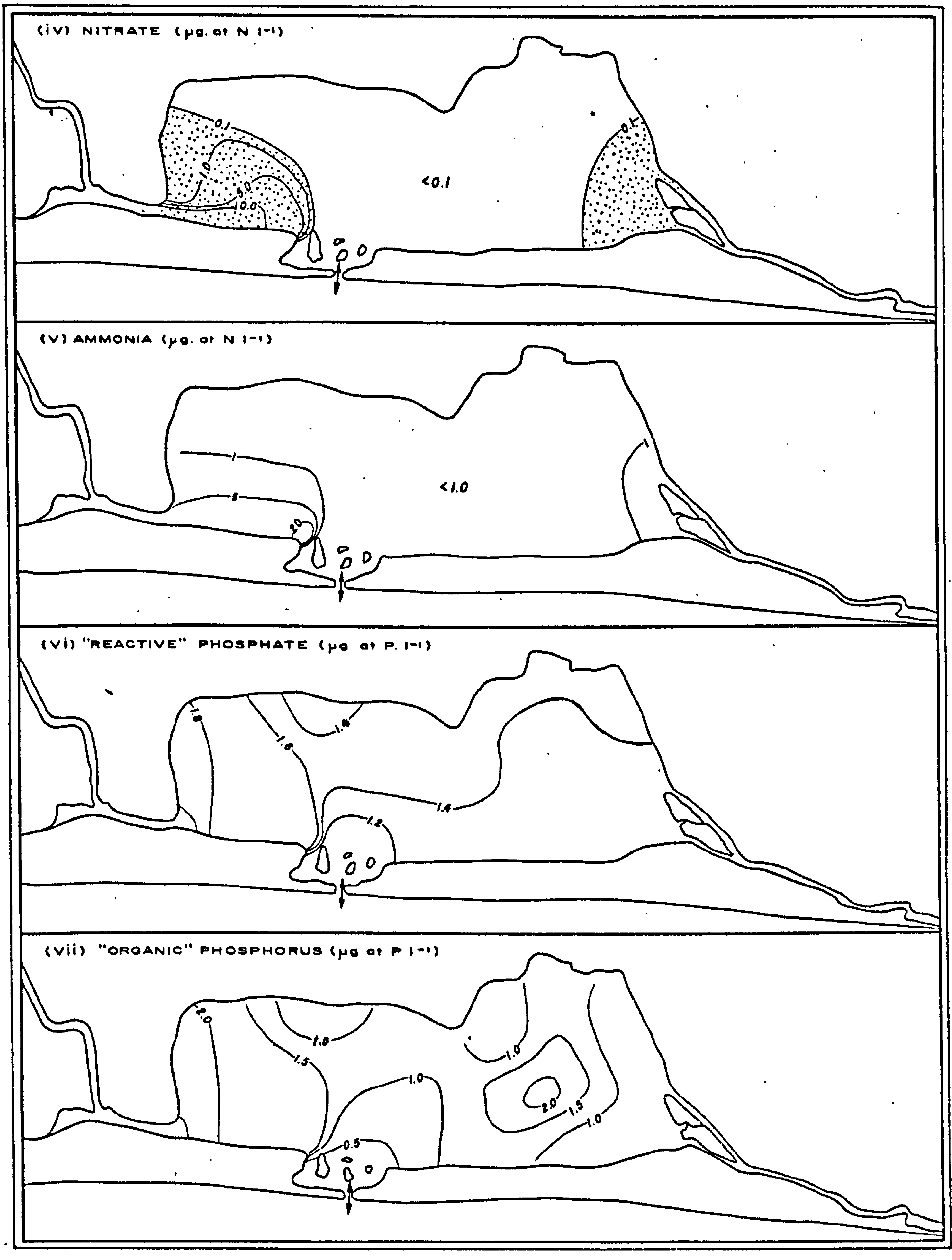
(iii) CHLOROPHYLL a (mg m^{-3})

LAGUNA CHAUTENGO—GENERAL CHEMICAL PARAMETERS (I) JULY 1976 (SURFACE)

Figure 6.8

LAGUNA CHAUTENGO - GENERAL CHEMICAL PARAMETERS

(2) JULY 1976 (SURFACE).



(iv) NITRATE (μg. at N l^{-1})

(V) AMMONIA (μg. at N l^{-1})

(vi) "REACTIVE" PHOSPHATE (μg at P. l^{-1})

(vii) "ORGANIC" PHOSPHORUS (μg at P l^{-1})

LAGUNA CHAUTENGO–GENERAL CHEMICAL PARAMETERS (2) JULY 1976 (SURFACE)

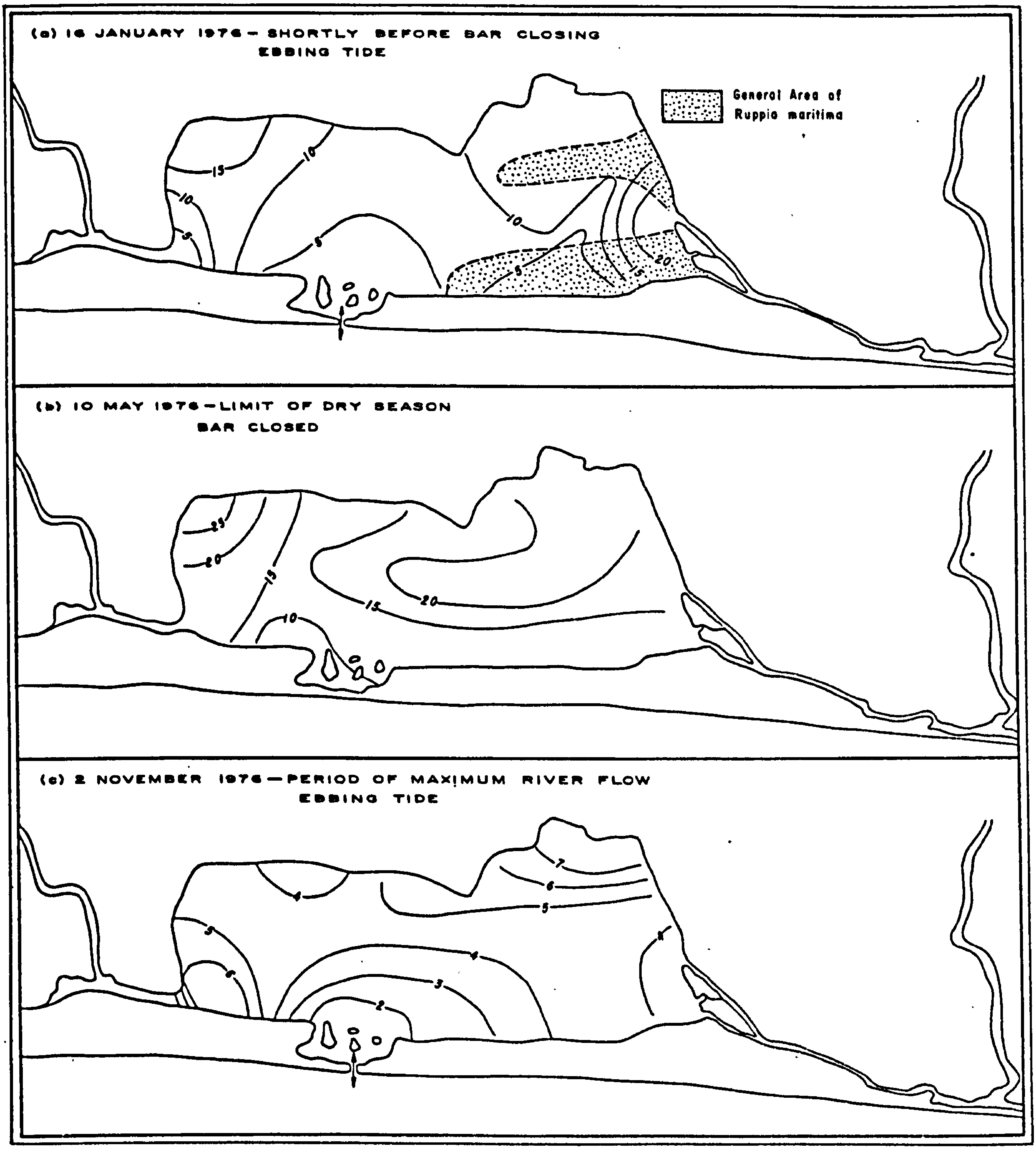
The distribution of reactive and 'organic' phosphorus does not exhibit the strong river plume seen for the inorganic nitrogen nutrients. This difference is probably a result of strong uptake of the inorganic nitrogen nutrients as some of the water mixes towards the north. In the case of phosphorus, the northwards mixing is reflected in the resultant phosphorus nutrient values and the river plume appears to be wider. The concentration of reactive phosphate is lower in the eastern basin of the lagoon, than in the western basin and there is no plume of phosphorus nutrients associated with the Rio Copala discharge. The general observation may be made that the effect of the Rio Copala on nutrient concentrations in the lagoon is always considerably less than that of the Rio Nexpa. This may result from the fact that the Rio Copala passes through a large area of mangroves which would be expected to take up nutrients, directly, or indirectly from the river water. In contrast, the Rio Nexpa is not associated with extensive mangrove areas. For the case of organic phosphorus, the highest concentrations in July were associated with the Rio Nexpa discharge with the exception of a localised high value at station 5 in the east of the lagoon. The latter value was also associated with a silicate minimum, suggesting a patch of high production and excretion.

The three seasonal examples presented above illustrate the general features of the distribution of nutrients and chlorophyll$_a$ during the three major stages of the lagoon cycle. Some additional features are illustrated on fig. 6.9 which presents the chlorophyll$_a$ distribution during the January, May and November surveys. The January and November surveys show the basic distribution reported for the July survey. In both cases an area of low chlorophyll$_a$ levels marks the area of direct exchange of lagoon and sea water. The effect of both rivers may be observed and also of the mixing of the Rio Nexpa water towards the north. The chlorophyll$_a$ levels for the January survey were generally higher than those for November, despite the larger river flow in the latter case. This may reflect a lowering of the concentration of nitrogen nutrients in the river when its flow is increased coupled with the effect of the increased river flow in increasing the export of suspended particulate matter from the lagoon.

During the January survey a large area of *Ruppia maritima* (sea grass) beds was observed. The approximate extent of these beds is shown in fig. 6.9. In order to obtain a rough idea of the biomass of these beds, two 1 m^2 quadrants of the grass were cut and their weight measured following washing and freeze-drying. The average dry weight was about 250 g/m^2. Subsequent carbon and nitrogen analyses of sub-samples showed them to contain ca. 34% Carbon and 3.4% Nitrogen (by weight). This would represent a reservoir of approximately 85 g/m^2 of Carbon and 8.5 g/m^2 of Nitrogen in the *Ruppia* beds. Following bar closure the beds began to break up and large quantities of the decaying plants were observed both floating in the lagoon and deposited along its northern shoreline. The factors causing the death of the plant beds are not known. Gradual decay of the dead plants may have provided an important source of nutrients to the lagoon in subsequent months.

The chlorophyll$_a$ distribution for the May survey was very similar to that observed in the preceding month. The area of highest chlorophyll$_a$ does not appear to be associated with any river discharge and the possibility exists that this characteristic

Figure 6.9
LAGUNA CHAUTENGO
SEASONAL COMPARISON OF DISTRIBUTION
OF CHLOROPHYLL $_a$



LAGUNA CHAUTENGO- SEASONAL COMPARISON OF DISTRIBUTION OF SUSPENDED CHLOROPHYLL a
(mg m^{-3})

distribution may be associated with areas of differing nutrient regeneration which is the only other possible source of limiting nutrients.

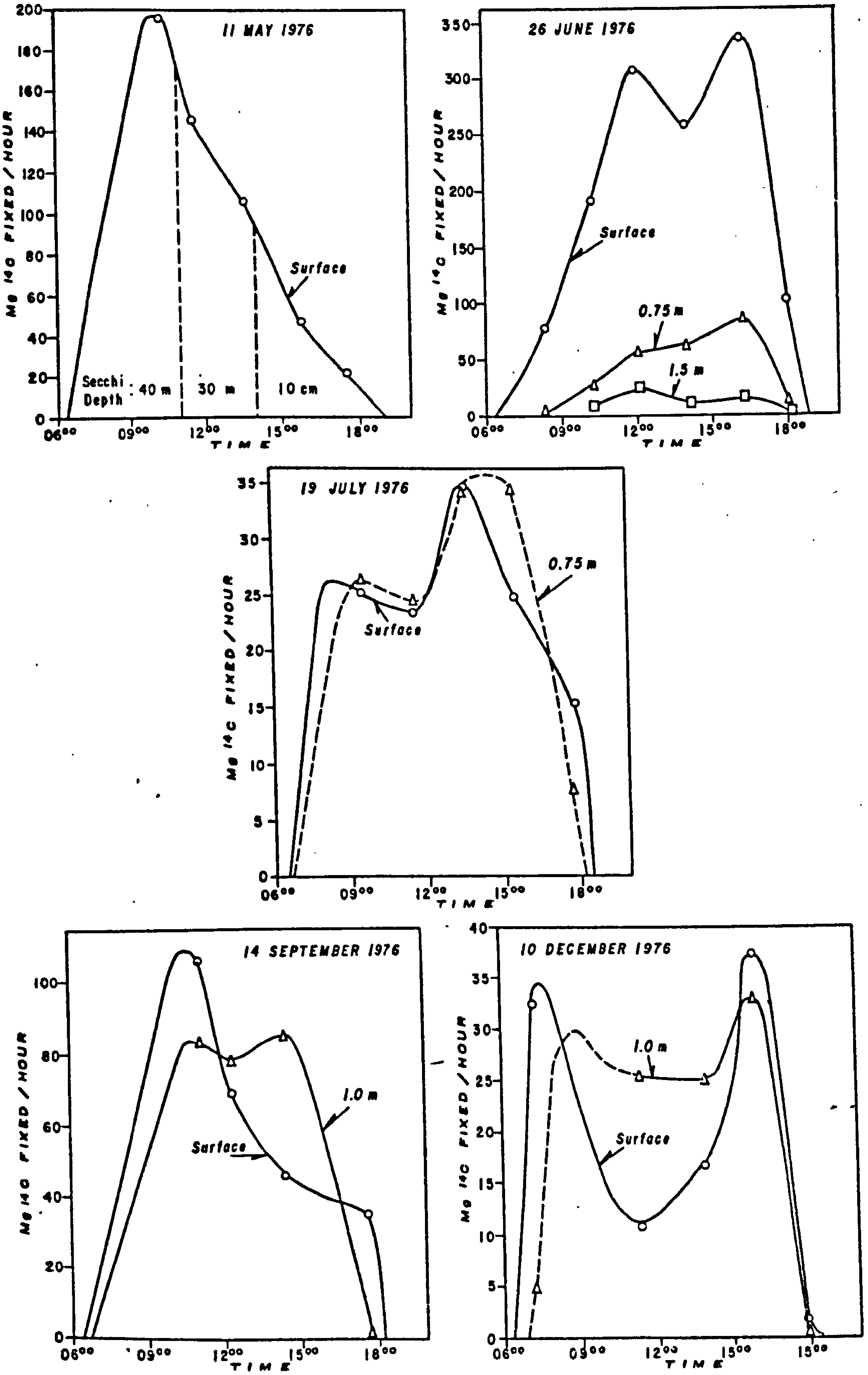
6.2.2 Primary productivity

Studies of primary productivity were conducted in the Laguna Chautengo (station 3) and the Laguna Mitla.

Productivity curves for the Laguna Chautengo are shown in fig. 6.10. The first experiment was conducted during the May survey when the lagoon was at its shallowest. The 'surface' measurements were made at a depth of about 5 cm. Following a high morning productivity, the productivity steadily declined throughout the day until dusk. This observation probably results from a combination of two factors. The first is inhibition by the intense mid-day sunlight (observed in the other measurement of the present study) and the second is the greatly increasing turbidity of the water during the afternoon. This was caused by sediment material suspended by wave action due to the afternoon sea breeze and was illustrated by the decreasing Secchi disc readings shown in fig. 6.10. This effect has previously been shown as a major factor limiting productivity in some coastal lagoons (Nichols 1966).

The second study was conducted ten days after the June general survey and one or two days before bar opening. Early morning productivity was inhibited by heavy cloud cover. Some surface light inhibition may be seen around 14.00 hours, followed by a second productivity maximum at about 16.30 hours. The greater depth of water during this survey prevented afternoon sediment re-suspension. The effect of shading restricted the productivity

Figure 6.10
LAGUNA CHAUTENGO
STATION 3
^{14}C PRODUCTIVITY CURVES



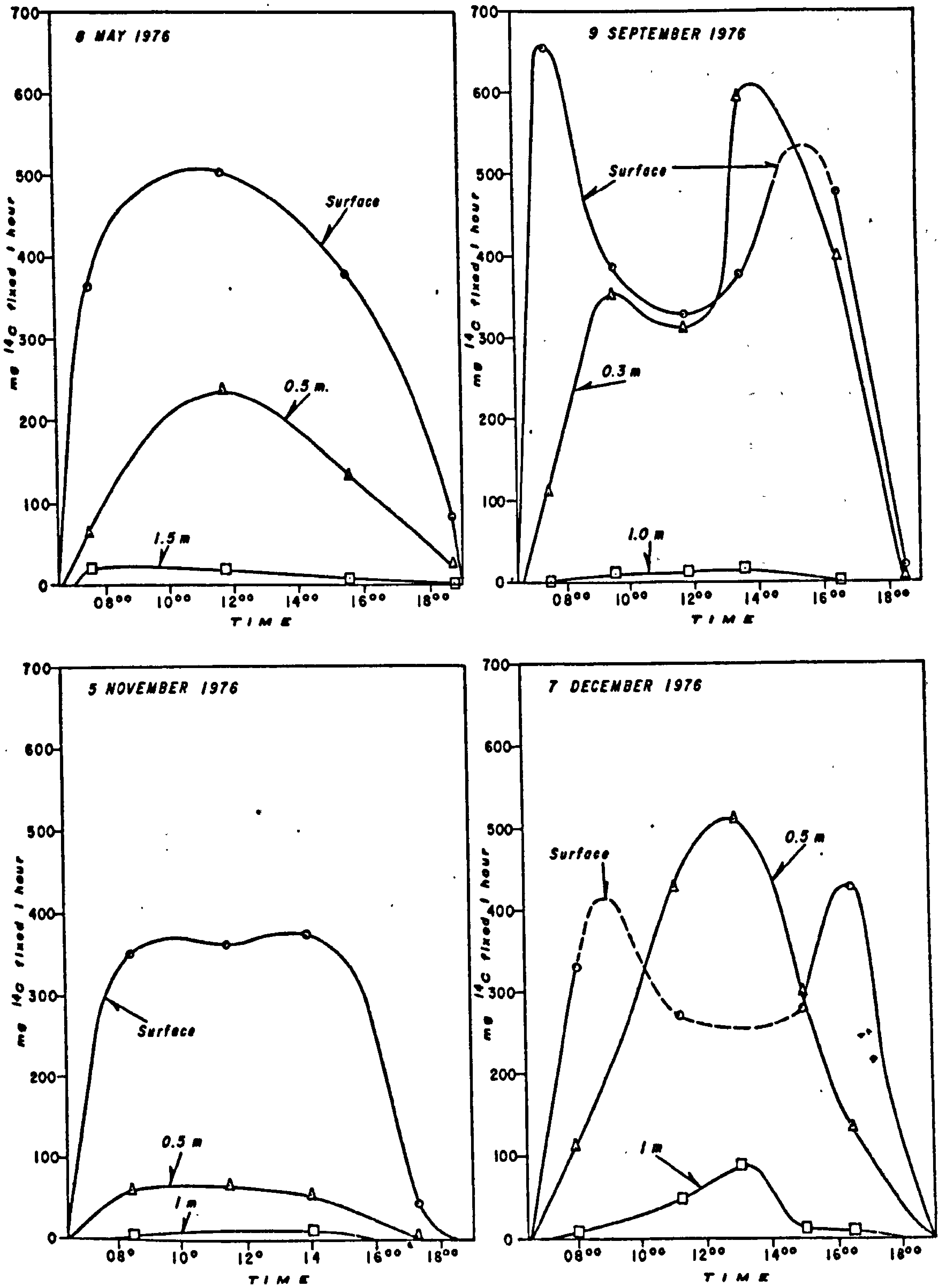
LAGUNA CHAUTENGO–STATION 3 — ^{14}C PRODUCTIVITY CURVES

NOTE: VERTICAL SCALES DIFFER BETWEEN DIAGRAMS at 1.5 m to only 4% of the surface value. The shading was probably largely self-shading by the large standing crop observed during the June survey.

The July study followed opening of the bar and the subsequent reduction in the standing crop of phytoplankton. Surface and 0.75 m productivity curves are almost identical, resulting from the clearer water of the lagoon. The September study shows a higher productivity level than in the July study but with similar productivity values for the surface and 1 m experiments. The surface curve exhibits the effects of strong light inhibition with limited recovery in the afternoon. The December curves are similar to those of September, with light inhibition in both the surface and 1 metre experiments.

Productivity curves for the Laguna Mitla are illustrated in fig. 6.11. With the exception of the May curves, the diagrams clearly show the effect of surface light inhibition. A rapid decrease in the productivity with depth is evident from all of the studies. The 1 metre curve for September for example represents only 0.25% of the productivity measured in the surface experiment. This reduction is almost certainly due to self-shading by the very large population of phytoplankton which gave the entire lagoon a strong green appearance and reduced the Secchi depth to 20-30 cms. Sub-surface productivity curves did not, with the exception of the September study, show the effects of light inhibition. The similar magnitude of productivity in the May, September and December experiments may be clearly seen despite the different forms of the curves. The November productivity is clearly lower than that for the other studies.

Figure 6.11
LAGUNA MITLA
^{14}C PRODUCTIVITY CURVES



LAGUNA MITLA – ^{14}C PRODUCTIVITY CURVES

A comparison of the results of all the primary productivity studies is made in fig. 6.12. The bar diagrams show the estimates of ^{14}C productivity and the gross productivity and respiration (from the oxygen method) for the dates on which the studies were conducted.

For the Laguna Mitla, a similar pattern of results is observed from both the Oxygen and ^{14}C productivity estimates. The oxygen measurements show the highest productivity in January 1976 and February 1977, slightly lower values for May and September and the lowest value for the November study. The November study followed the heavy October rains which caused a large increase in the volume of the lagoon and its subsequent stratification. The respiration estimate for the study was significantly higher than that of productivity. 'Respiration' is rather loosely used here and refers both to the biochemical and chemical demand for oxygen in the system. This observation is very similar to that made by Odum et al (1963) for a lagoon area in Texas (U.S.A) where a heavily polluted ship canal discharges large amounts of detrital material with a large oxygen demand. It is suggested that a similar process is involved here, the discharge of detritus resulting from sudden reduction in the standing crop of phytoplankton. Further evidence to support this hypothesis will be presented later.

The seasonal pattern of productivity for the Laguna Chautengo is quite different from that of Mitla. The highest productivity was observed in the June study following the start of the rainy season and the input of fresh nutrients into the lagoon. The effect of exchange of sea water in the lagoon may be seen by the low productivity in the July and December studies. The location of the productivity measurement station (station 3) was chosen so as to be away from the direct effect of river run-off

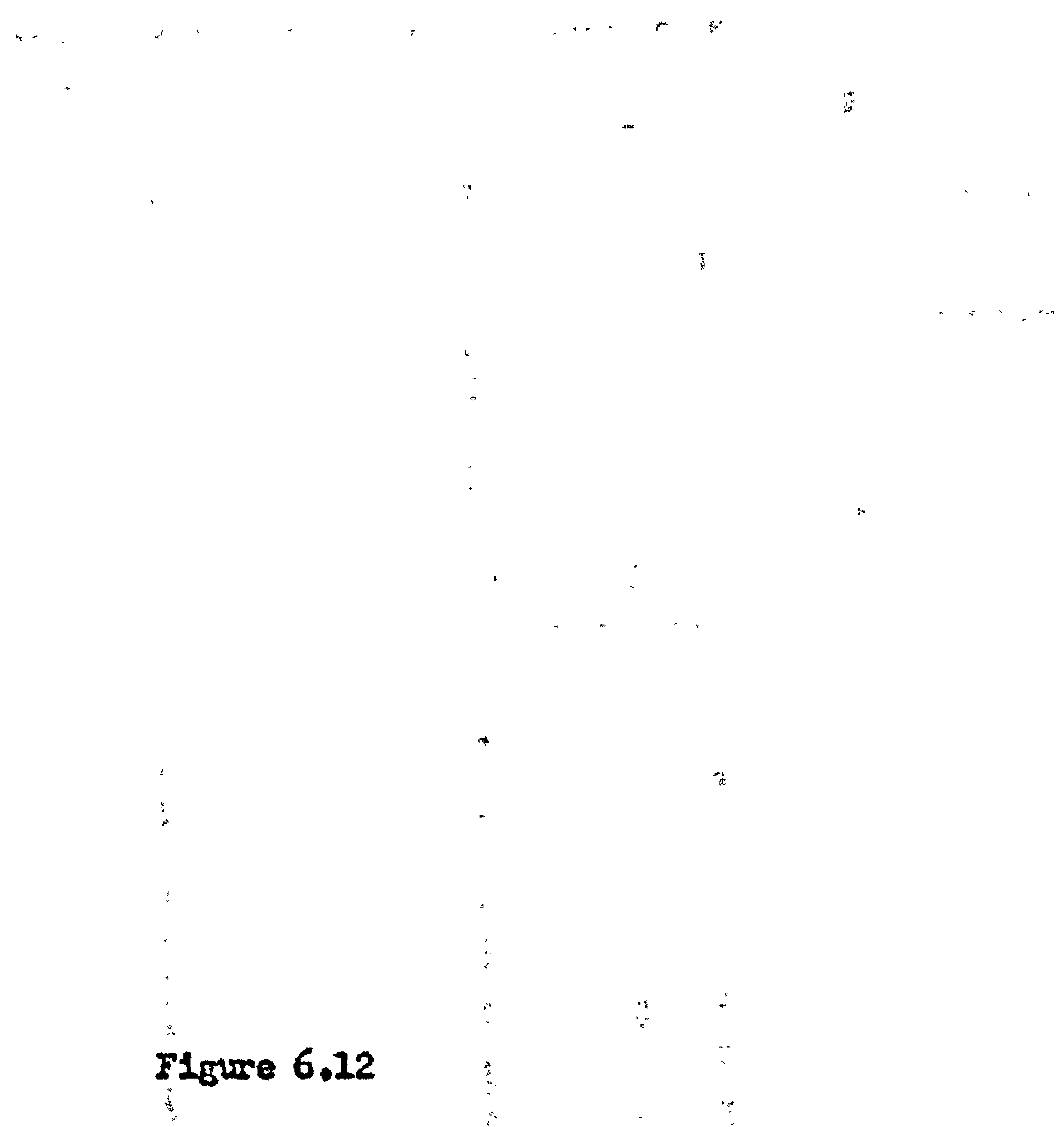
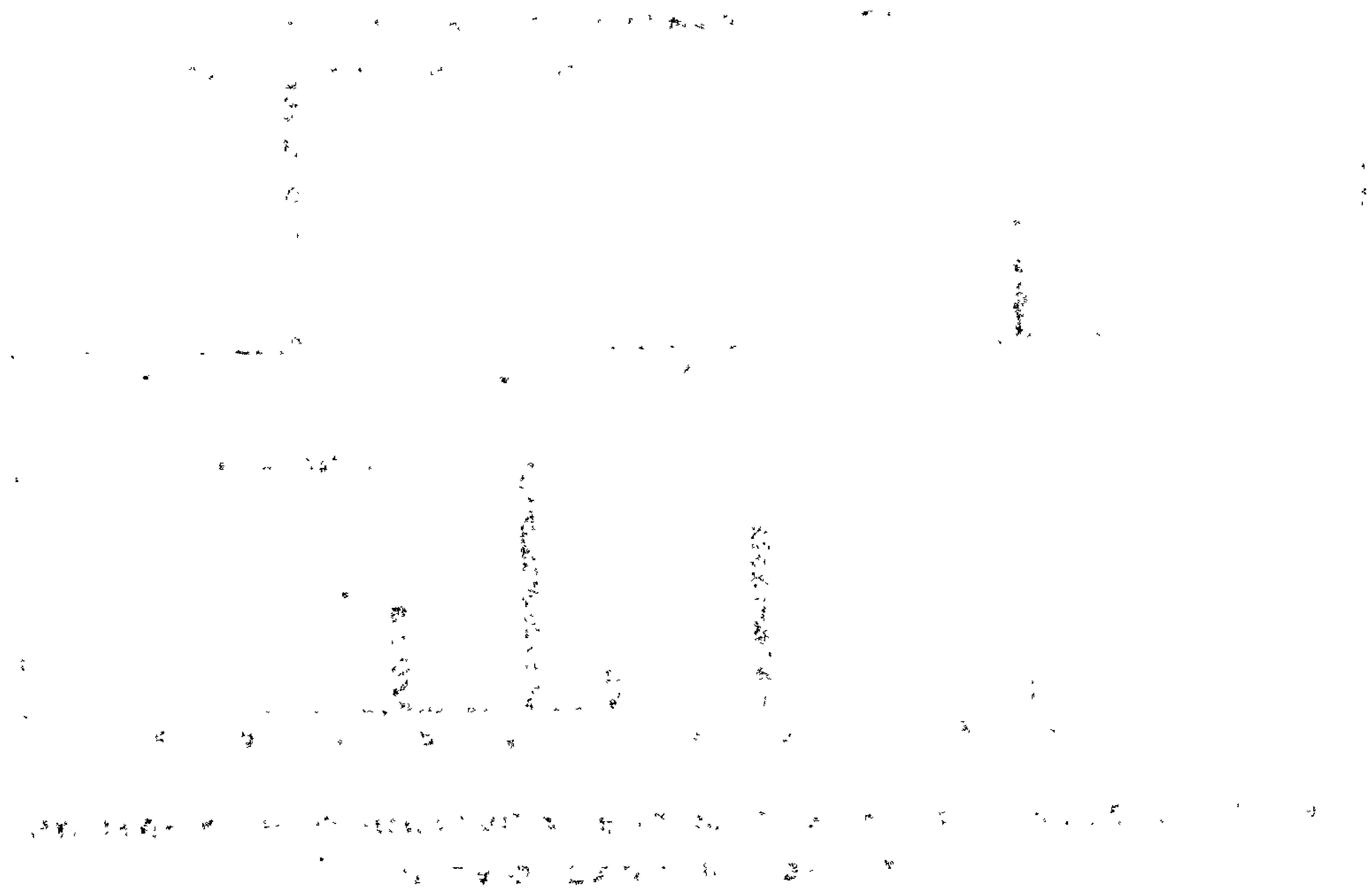
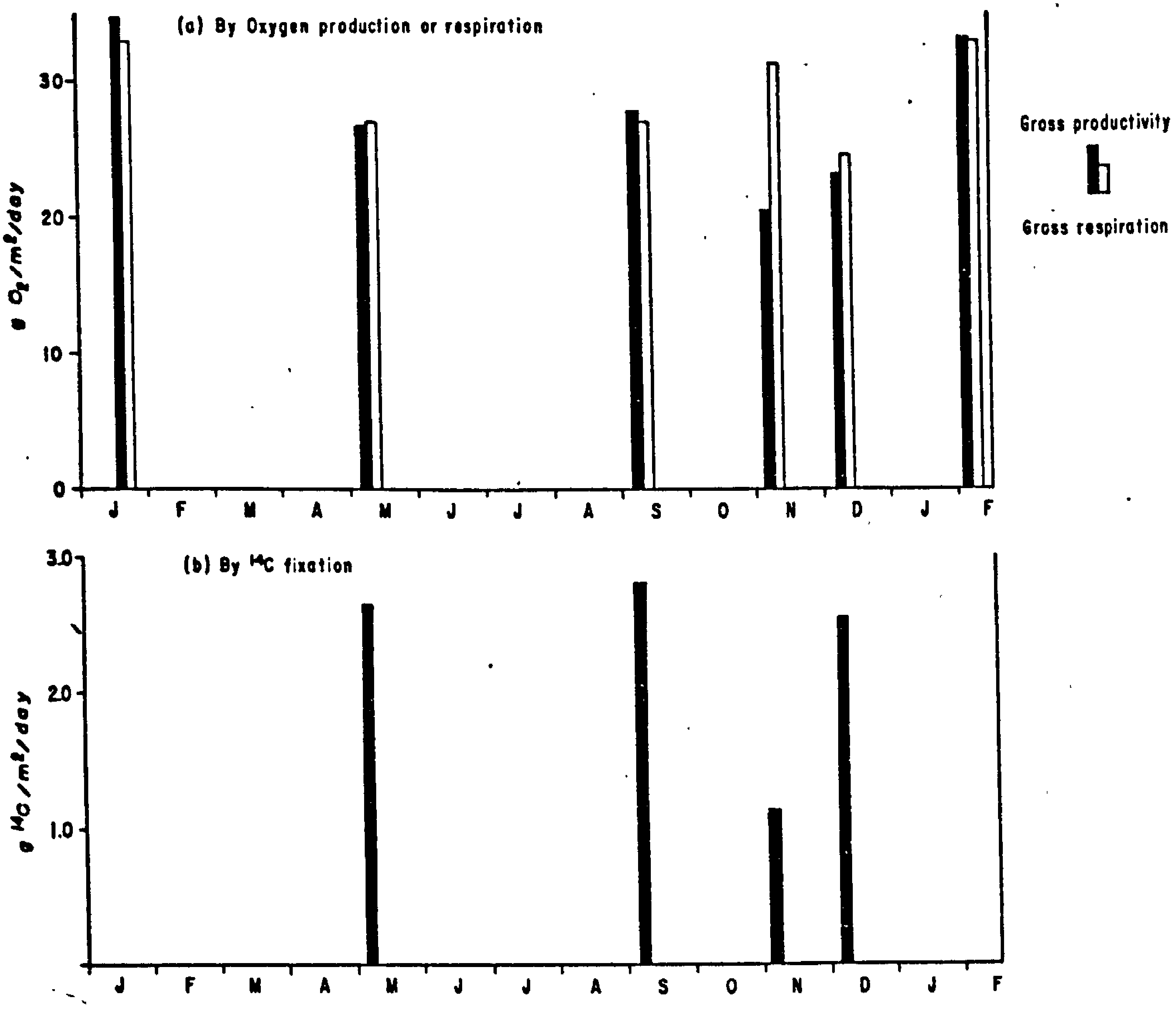


Figure 6.12

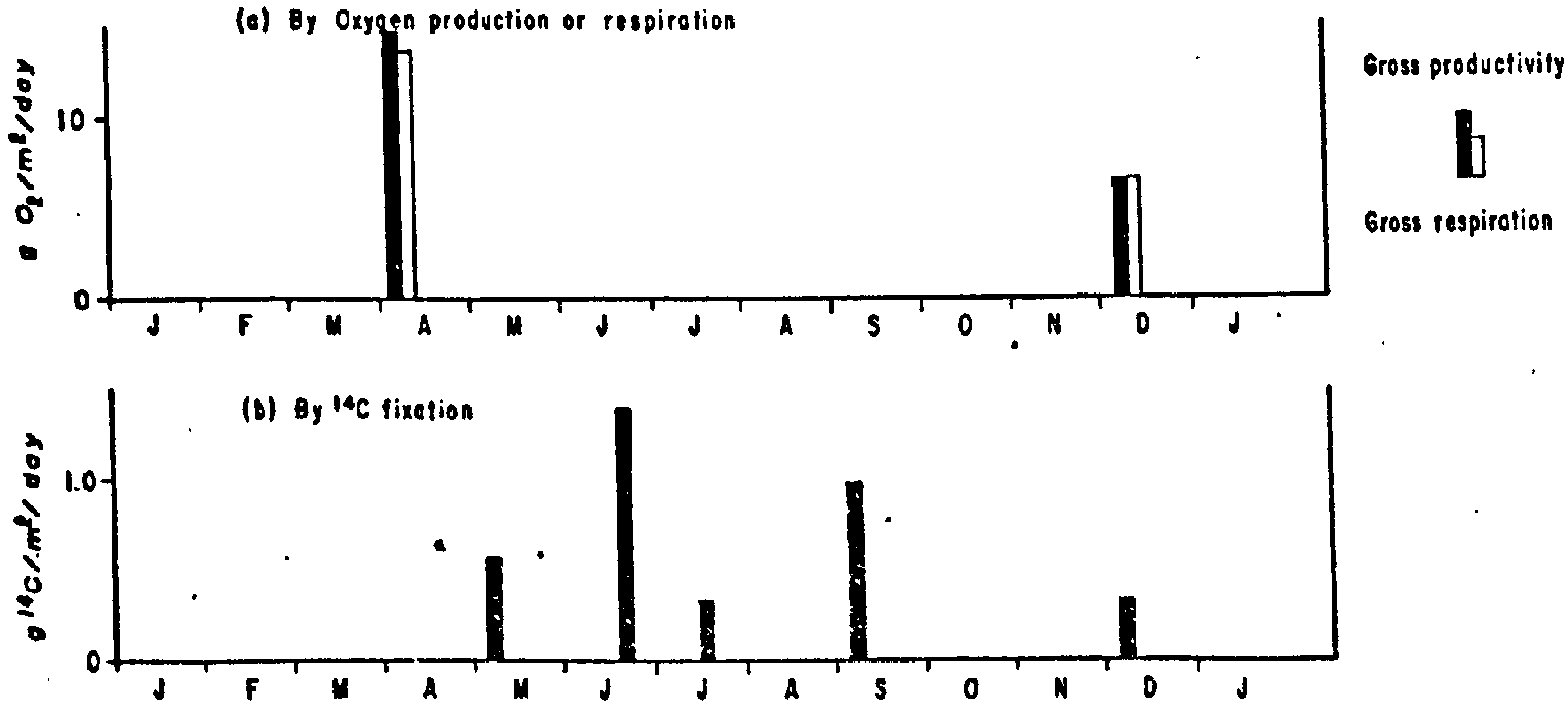
PRIMARY PRODUCTIVITY ESTIMATES AT A SINGLE STATION IN TWO LAGOONS (1976-77)



(1) LAGUNA MITLA, STATION "EL CAMALOTE"



(2) LAGUNA CHAUTENGO, STATION 3



PRIMARY PRODUCTIVITY ESTIMATES AT A SINGLE STATION IN TWO LAGOON (1976-77) and from the area of immediate tidal influence. The relatively high productivity in the September study probably reflects the increased river run-off in that month. The productivity estimates for May (^{14}C estimate) and April (O_2 estimate) are both about double the estimates for December. That is to say, the productivity for the period when the lagoon is isolated and with a negligible river input is roughly twice that for the period when the lagoon is communicated with the sea and receives a small river input. This illustrates the effect of bar closure in retaining dissolved and particulate material within the lagoon and the effect of regeneration within the closed lagoon system, maintaining a relatively high primary productivity despite the lack of external nutrient sources.

The primary productivity for the Laguna Mitla was much higher than that of the Laguna Chautengo, possibly reflecting the isolation of the former lagoon from the sea. No data is available regarding the primary productivity in the adjacent sea water. Values for the open ocean (Indian ocean) at the same latitude range from 0.06 to 0.43 gC/m^2/day with a mean value of 0.16 g C/m^2/day (Ryther et al 1966). Productivity in the Laguna Chautengo (station 3) was only slightly higher than this figure in July and December though it must be noted that the use of area-based productivity measurements to make such comparisons is misleading, the productivity in Chautengo is concentrated in a water column of 0.5 - 1.5 metres and that of the sea is often dispersed over more than 100 metres. Productivity estimates for Chautengo by the oxygen method are of similar magnitude to those in the Texas lagoons (Copeland and Nixon 1974). Estimates for Mitla are somewhat higher than those presented in the Texas studies.

A rough comparison of total chlorophyll$_a$ (representing the standing crop of phytoplankton) for the water column and the ^{14}C primary productivity has been made in table 6.3. The ratio of the two parameters gives an approximate idea of the relationship between the productivity and the standing crop that it is maintaining (assuming that the standing crop in the water column is being supported by production in the same water column).

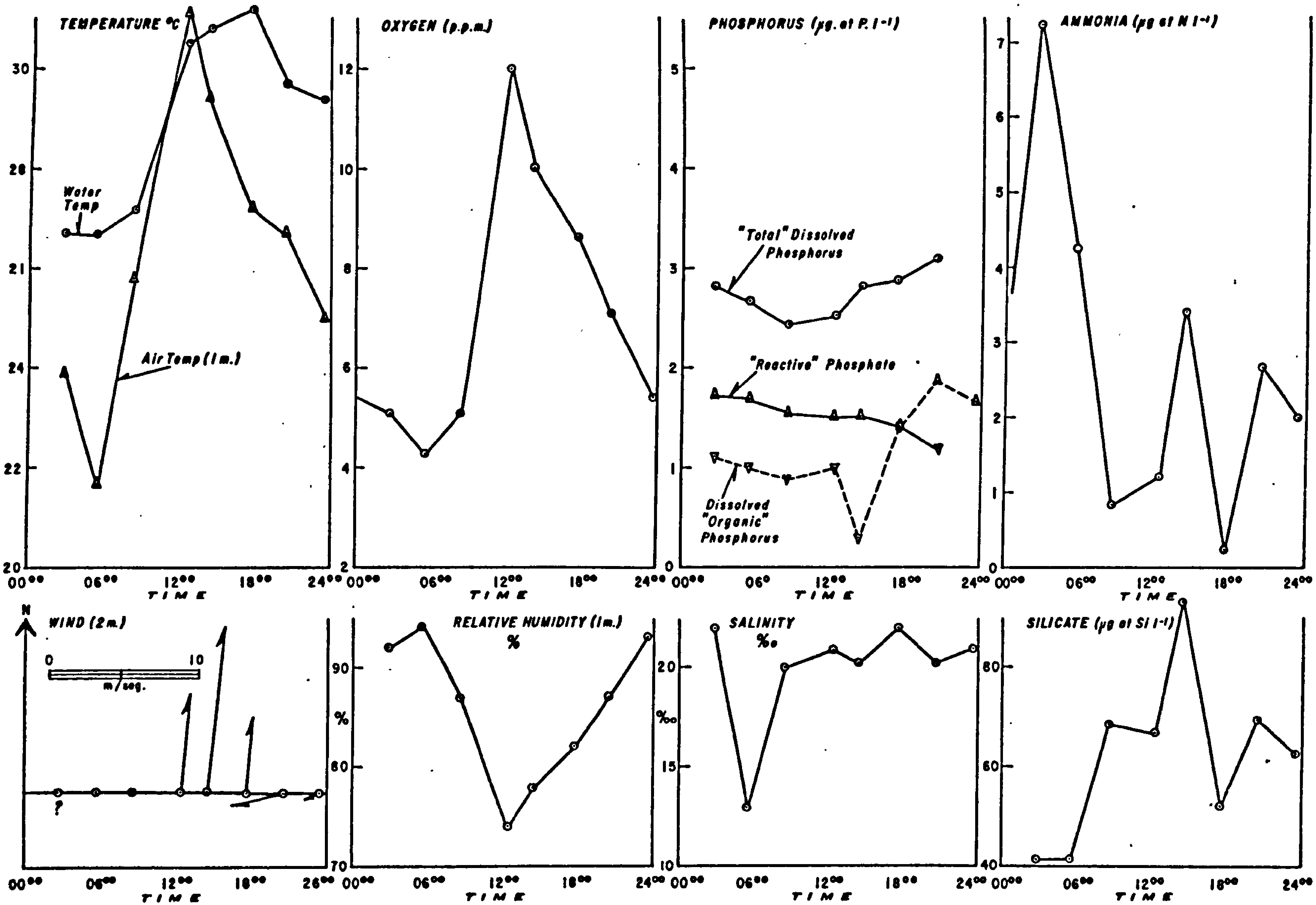
Table 6.3 - Comparison of productivity and chlorophyll estimates for stations in the Laguna Mitla and Laguna Chautengo.

	MITLA			CHAUTENGO		
Month of Study	Productivity $gC/m^2/day$	Chlorophyll g/m^2	Ratio	Productivity $g\ C/m^2/day$	Chlorophyll g/m^2	Ratio
May	2.7	0.68	3.9	0.6	0.012	47.5
June	-	-	-	1.4	0.031	45.2
July	-	-	-	0.32	0.003	107.
Sept.	2.8	0.65	4.3	0.98	0.0075	131.
Oct/Nov.	1.1	0.20	5.5	-	-	-
Dec	2.6	0.51	5.0	0.33	0.0015	220.

Lower values in the ratio indicate lower productivity/unit of standing crop providing that the species composition does not change. For the case of Mitla where, according to Licea *et al* (1976) there is a continual bloom of Cyanophyta throughout the

Figure 6.13

24 HOUR STATION - CHAUTENGO STATION 3
5th APRIL, 1976



24 HOUR STATION – CHAUTENGO STATION 3, 5 APRIL 1976

would seem rather surprising since maximum Oxygen values are normally attained towards sunset. The lack of high Oxygen production during the afternoon period however, probably reflects the effect of sediment suspension and surface light inhibition of productivity that was demonstrated for the May productivity study.

The results of phosphorus analyses show a small, but rather inconclusive variation. A steady, though very small decrease in the reactive phosphate concentration was observed throughout the day, possibly indicating increased uptake of orthophosphate by photosynthetic organisms during production.

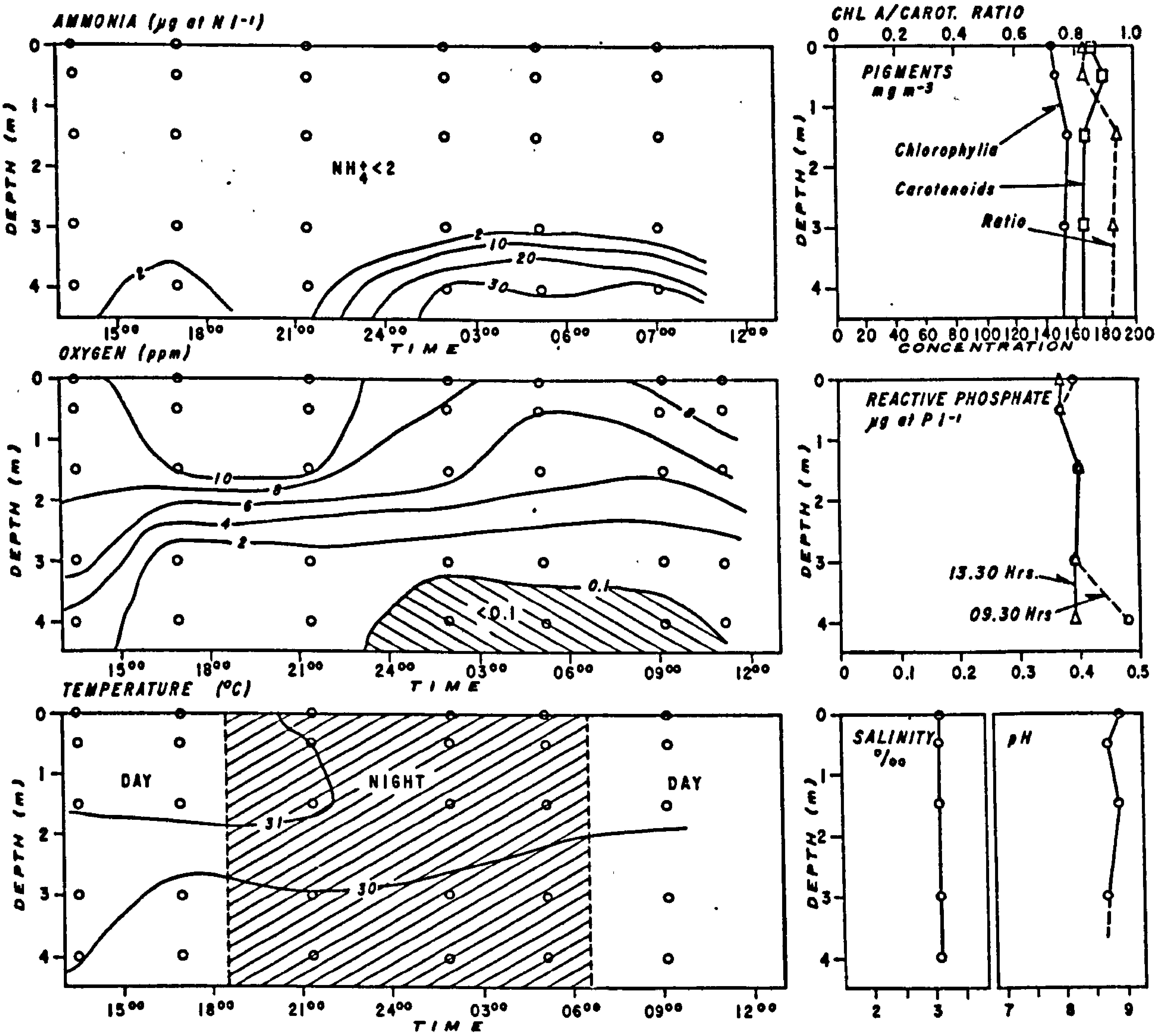
A comparison of the shapes of the ammonia and silicate curves shows a similar pattern of variations after 0800 hours, almost certainly resulting from water movements. The ammonia curve before dawn however, exhibits a large maximum which may result from the regeneration of ammonia during the night coupled with the limited ammonia uptake during the might period.

Whilst the data in fig. 6.13 are not conclusive they do suggest that diurnal variations in nutrient concentrations may be an important factor in the chemistry of a lagoon.

temperature, the oxygen concentration and the ammonia concentration are plotted with respect to depth and time. Additional diagrams show depth profiles of pigments, phosphorus salinity and in one case, pH. General features of each of the diagrams will be presented and finally the system will be discussed as a whole.

Fig. 6.14 shows the diurnal variations for a study in May 1976. The lagoon depth was 4.5 metres and the study was conducted towards the end of the dry season. The temperature

Figure 6.14
LAGUNA MITLA
24 HOUR STATION
8th MAY 1976



24 HOUR STATION-LAGUNA MITLA-8 MAY 1976

shows the type of variation discussed in Chapter 5, with the minimum temperatures around dawn. The oxygen diagram shows the effect of high daytime production near the surface and a high oxygen demand during the night. The bottom water, during the latter part of the night and early morning became completely anoxic due to the high oxygen demand coupled with the limited oxygen supply to it during the day.

The ammonia concentration in the lagoon was generally below 2 µg at N l^{-1}. During the night however, high ammonia production was observed in the bottom water, coinciding with the anoxic region.

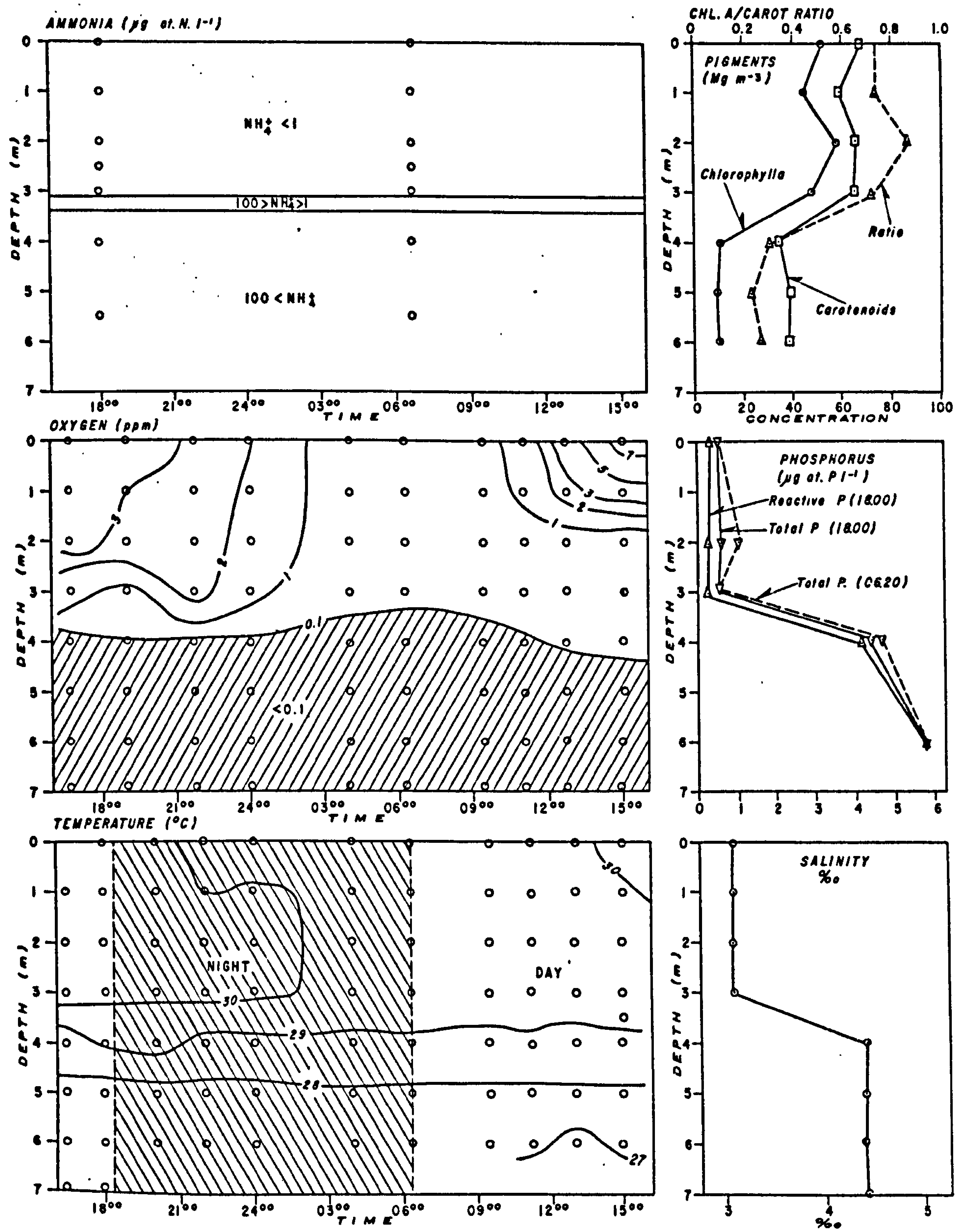
The concentration of suspended pigments was found to be practically uniform throughout the water column. Similarly other parameters (Salinity, pH and phosphate) were found to be practically homogeneously distributed. A small phosphate maximum was observed in the bottom water during the anoxic period.

A 24 hour study of oxygen and temperature variations in September was presented in fig. 5.9. This showed very similar features to the May survey but with a longer period of anoxic conditions, affecting the bottom 1-1½ metres for 18 hours from 19.30 hours until 13.30 hours the following day.

The November study (fig. 6.15) followed the large run-off into the lagoon during October and the water depth during this study was 7 metres. The temperature diagram shows the usual pattern of surface heating throughout the day and cooling at night. Below 3½ metres however, the water column may be seen to be stratified throughout the 24 hour period.

The oxygen diagram shows the daytime production of

Figure 6.15
LAGUNA MITLA
24 HOUR STATION
4-5 NOVEMBER 1976



24 HOUR STATION - LAGUNA MITLA 4-5 NOVEMBER 1976

oxygen and very low oxygen values, even in the surface waters, during the night. The water below 4 m was completely anoxic during the entire study and water samples smelled strongly of hydrogen sulphide. The very low oxygen values during the day and night suggest a very high oxygen demand in the water column. The differentiated oxygen curve drawn for the calculation of productivity by the oxygen method (fig. 6.18) exhibited a sloping respiration line, suggesting that the respiration during the first part of the night was higher than that during the period just before dawn. It is possible that the respiration just before dawn was limited by the rate of oxygen diffusion into the water column.

Both ammonia and dissolved phosphorus levels were very high below 3-3½ metres. The maximum level of ammonia recorded was 320 ug at N l^{-1} and of phosphate (the predominant form of dissolved phosphorus in the anoxic region), 5.8 ug at P l^{-1}.

The pigment profiles exhibit a reasonably uniform distribution down to three metres where there is a rapid drop in the chlorophyll concentration to ca 10 mg/m^3 after which it remains uniform throughout the anoxic layer. The chlorophyll/carotenoid ratio also drops very rapidly between the 3 to 4 metre depths, illustrating the decay of cells falling into the anoxic water. The integrated $chlorophyll_a$ level for the water column (204 mg/m^2) is considerably lower than that for the September survey (646 mg/m^2) indicating a large reduction in the standing crop.

In view of the anoxic conditions below 3 - 4 metres, it is difficult to determine whether the salinity values illustrated in fig. 6.15 are an accurate reflection of salt water stratification or are an artifact of the chemical conditions of the anoxic zone.

The data from the December study (fig. 6.16) is in many respects similar to that of the previous month. However it can be seen that the temperature stratification was not as pronounced as in the previous survey and the division between oxygenated and anoxic conditions was not as clearly defined.

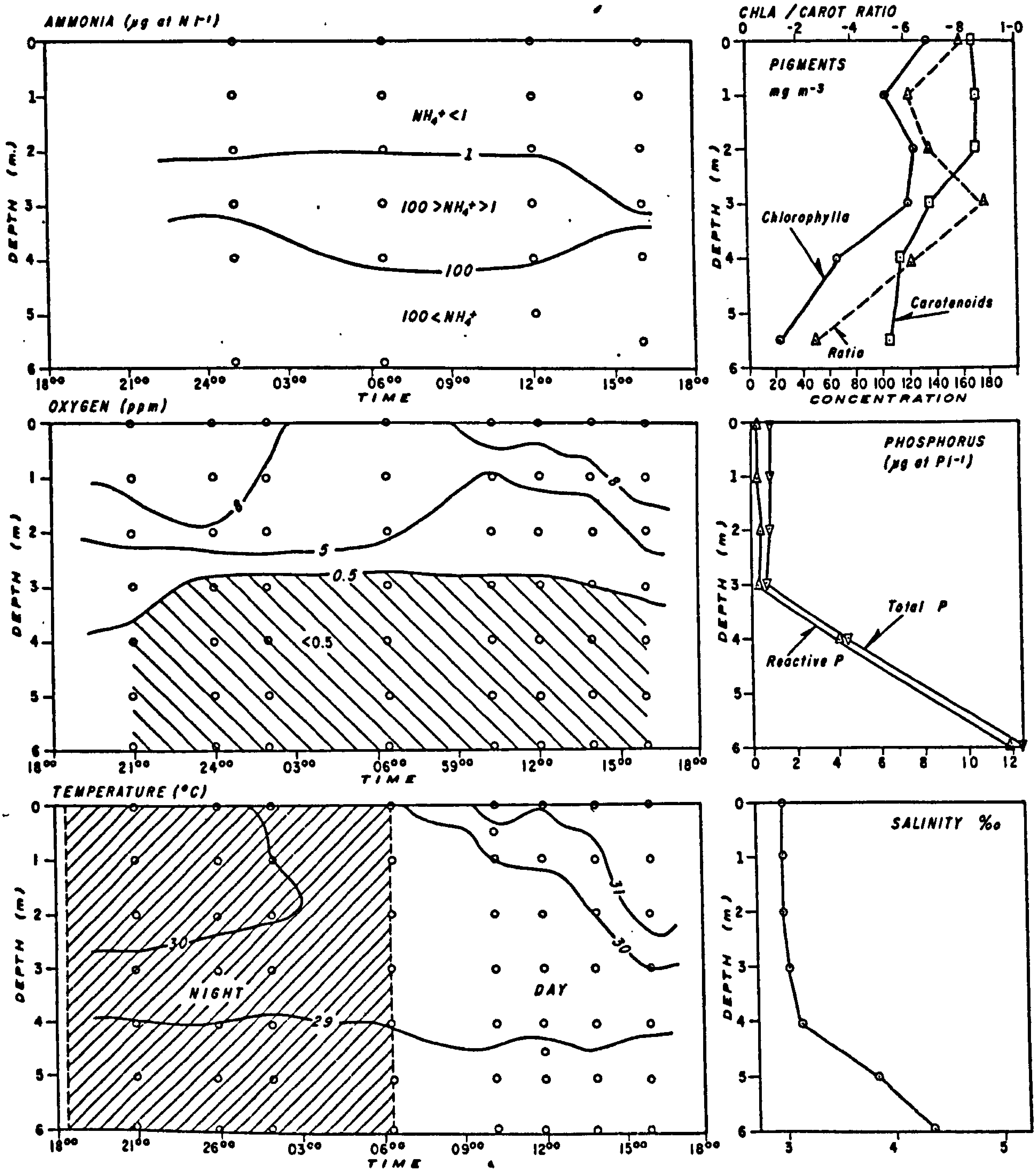
Various factors contribute to this observation. The depth at which anoxic conditions was observed showed a diurnal variation with the maximum depth of oxygenated water found during the afternoon (as in the surveys of May and September though not reaching to the bottom of the lagoon). The change from very low to very high ammonia and dissolved phosphorus was not as clearly marked (in the area marked $100 > NH_4^+ > 1^{-1}$, concentrations of between 21 and 81 μg at N 1^{-1} of ammonia were found). Finally the pigment profile did not undergo such a sudden change on entering in anoxic conditions, only the bottom 2½ metres of which appeared to contain hydrogen sulphide.

The bottom water adjacent to the sediment/water interface during the December study exhibited higher nutrient concentrations than in the previous month with a maximum ammonia concentration of 840 μg at N 1^{-1} and a maximum phosphate concentration of about 12 μg at P 1^{-1}.

Oxygen concentrations in the upper water column had risen to higher levels than in the previous month and very low night-time values were not found in this study. The total chlorophyll a level had also risen to 520 mg/m^2 showing partial recuperation of the standing crop.

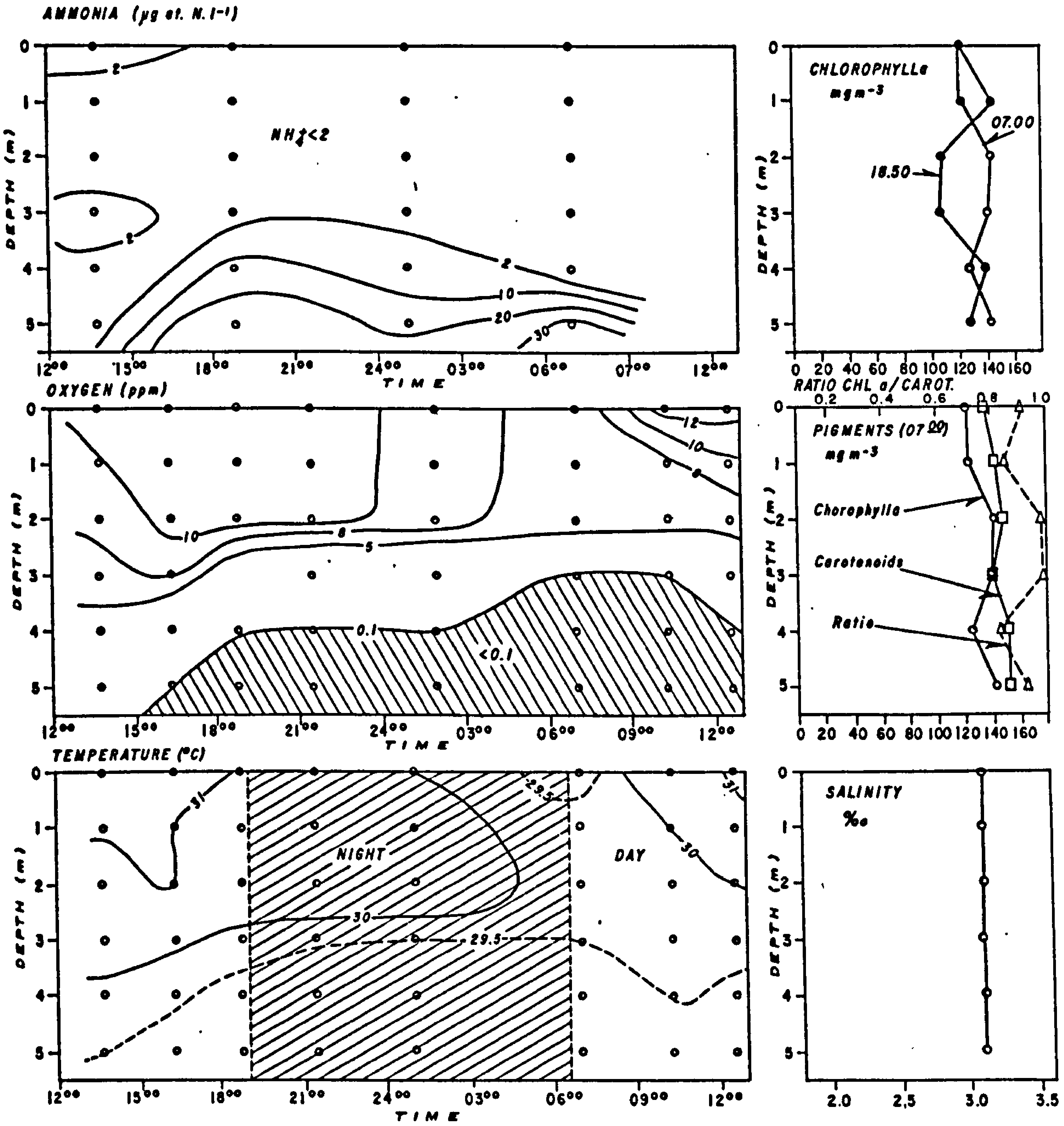
By the time the final study was undertaken in early February 1977, the water column had completely returned to the state observed in May and September. Fig. 6.17 illustrates the

Figure 6.16
LAGUNA MITLA
24 HOUR STATION
7 - 8 DECEMBER 1976



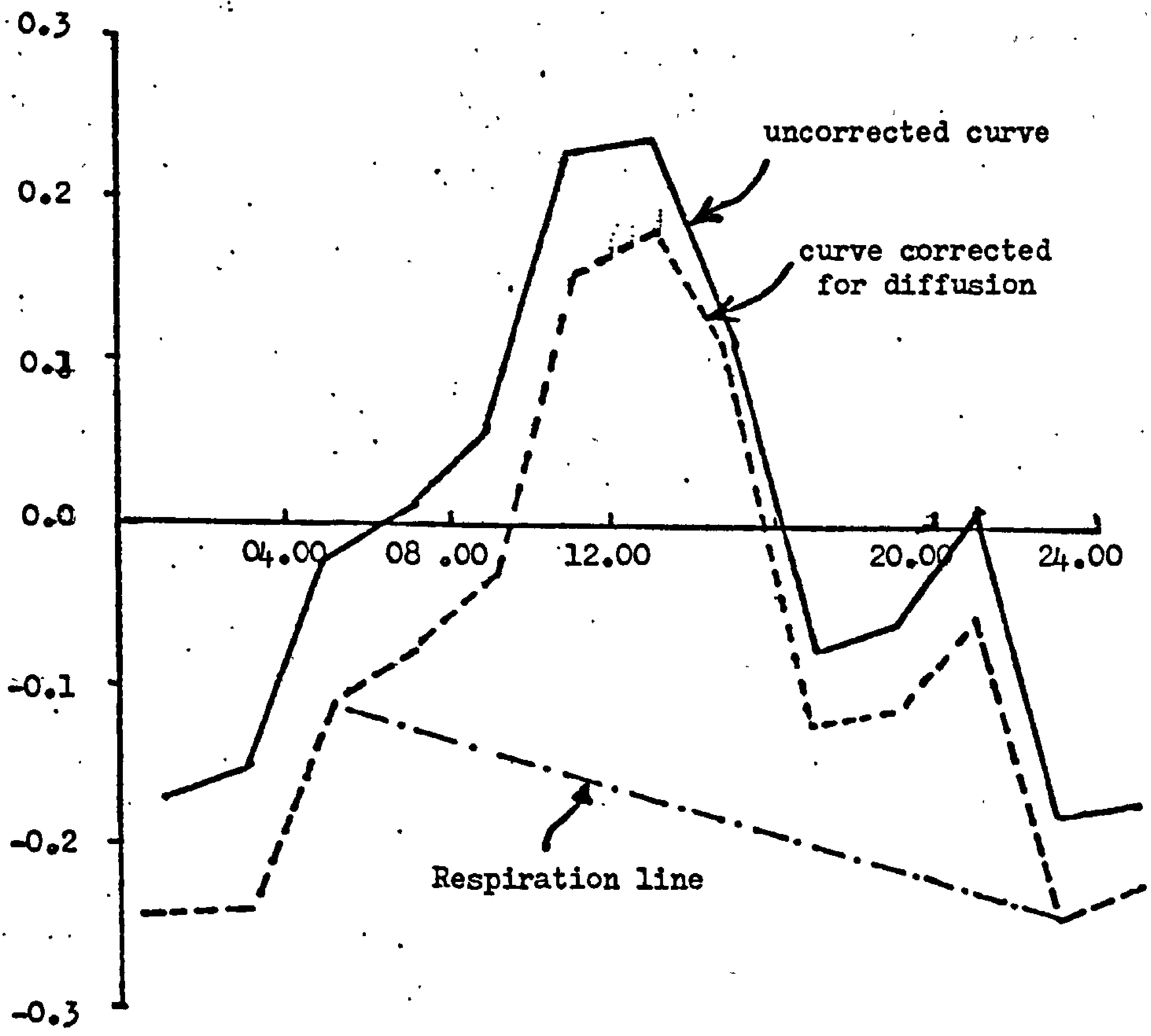
24 HOUR STATION – LAGUNA MITLA 7-8 DECEMBER 1976

Figure 6.17
LAGUNA MITLA
24 HOUR STATION
7 - 8 DECEMBER 1976



24 HOUR STATION-LAGUNA MITLA-2-3 FEBRUARY 1977

Figure 6.18
EFFECT OF HIGH OXYGEN DEMAND
ON THE P - R CURVE
(see APPENDIX 2)


0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
04.00
08 .00
12.00
20.00
24.00
uncorrected curve
curve corrected
for diffusion
Respiration line

data obtained for the February study. A long period of anoxic bottom water conditions was observed as in the September study. No large concentration of hydrogen sulphide was observed and the anoxic conditions were accompanied by ammonia production, with a concentration gradient indicating higher ammonia levels towards the sediment/water interface. Both pigments and 'salinity' (conductivity) exhibited a very uniform distribution with depth, as in the May survey.

The source of the ammonia produced in each of the surveys appears to be from its regeneration as part of the process of breakdown of cellular material and metabolic products. The increase in ammonia as the sediment/water interface is approached, may indicate regeneration from material collecting on it. The ammonia regeneration process must be bacterially mediated. Part of the process of cell breakdown may be carried out by benthic organisms, notably ostracods, of which there is a large population (Martinez et al 1976). It seems unlikely that the ostracod population could survive the long period of stratification through October and December, especially in the presence of hydrogen sulphide. Even in order to survive the short diurnal periods of anoxic conditions during the rest of the year they must be able to tolerate very low oxygen levels.

In order to investigate the recycling process in greater depth it was necessary to establish the relationship between Nitrogen, Carbon, Phosphorus and Chlorophyll$_a$ in the standing crop. Results of quadruplicate analyses of a surface sample indicate the following relationship :-

C:N:P = 191 : 27 : 1

C: Chl_a = 214 : 1

C: N = 7 : 1

P: Chl_a = 1.1 : 1

N: Chl_a = 31: 1

(which are very different from those encountered in the open sea but probably relate to the special encountered in this lagoon).

These ratios may be used to investigate the carbon and phosphorus equivalents of the ammonia and phosphate produced in the anoxic waters. For the May and February surveys, the net ammonium stock was ca 0.5 g N/m^2 and ca 0.45 g N/m^2 respectively. This illustrates the rapid production of ammonia in the bottom 1½ metres of the lagoon during the night. Using the above ratios the carbon and chlorophyll equivalents were calculated. Table 6.4 compares the ammonia production with the amount of suspended organic material (represented by carbon and $chlorophyll_a$) that would have been broken down to release it. This assumes that the lagoon was in overall equilibrium and that there were no external sources of detritus nor dissolved nutrients at the time of the studies. Since the studies were conducted during the dry season, this assumption is reasonable.

Table 64 - The significance of diurnal ammonia production in a water column during two studies in the Laguna Mitla.

	May study	Feb. study
Ammonia production	0.5g N/m^2	0.45g N/m^2
Equivalents, based on the suspended organic material		
Carbon	3.4g/m^2	3.2g/m^2
Chlorophyll$_a$	0.016g/m^2	0.015g/m^2
Features of the water column		
Total Chlorophyll$_a$	0.676 g/m^2	0.728g/m^2
Net productivity	2.65gC/m^2/day	-
Gross productivity *	20.43gC/m^2/day	25.5gC/m^2/day

* The conversion factor $138O_2 = 106C$ has been used (Richards 1965)

From the table it may be seen that the carbon equivalent of the ammonia produced is of about the same magnitude as the daily net productivity. This exemplifies the overall equilibrium of the system and suggests that the dissolved nutrients from the material decomposed are returned to the water column, where they become available for subsequent uptake and hence maintain the large standing crop. Though this process explains the overall eutrophication of the water, the magnitude of ammonia production is insufficient to account for the large gross productivity which must be maintained by a rapid regeneration and uptake of nutrients within the water column. By comparing the 'chlorophyll$_a$

equivalent' and the total chlorophyll$_a$ (table 6.4) the overall daily change in the standing crop may be seen to be only about 2.4%. Since the zooplankton population in the water column is very small (Martinez [illegible] 1976) it seems reasonable to suppose that grazing is very limited and that dead organisms fall through the water column to collect on the sediment/water interface. The high ammonia production during the night may only reflect a process of regeneration which continues throughout the day. Since no concentration gradient of ammonia was observed during the day it seems likely that any inorganic nitrogen regenerated would be immediately taken up despite the probable absence of photosynthesis below a depth of two metres. This rather curious observation, coupled with the limited mobility of the small (1 x 2 µm) Cyanophyta and the apparent viability of the cells below the photic zone (from the uniform profile of the chlorophyll$_a$/carotenoid ratio), suggests that there may be an active mixing process in the water columns during at least part of the day. Such a mixing process would reintroduce cells into the photic zone and transport regenerated nutrients from the lower water layer.

The complete stratification of the water columns which occurred between the September and November studies, resulted in a large decrease in the total standing crop. The dissolved nutrient increase in the water column would appear to result directly from regeneration of the nutrients previously bound in the proportion of the standing crop lost on stratification. The change may be shown as follows :-

Standing crop lost/m^2

Total chlorophyll$_a$ September study = 0.65 g
Total chlorophyll$_a$ November study = 0.21 g
Difference = 0.44 g

Nitrogen equivalent of difference = 13.7 g
Phosphorus equivalent of difference = 0.50g

Dissolved inorganic nutrients recovered/m^2

Ammonia (g.N) = 15.2 g
Phosphorus (g.P) = 0.58 g

The similarity of these figures suggests that the standing crop lost from the previous survey bacterially decomposed, under the anoxic conditions, finally releasing the equivalent concentration of inorganic nutrients.

The above presentation also illustrates the importance of mixing and diffusion in the water column. With the increase in depth of the water column and its stratification mixing processes were impeded and oxygen was required to diffuse over a greater distance. The high oxygen demand of the bottom water (and sediments) and the reduced supply of oxygen resulted in anoxic conditions forming. The limited mixing from the anoxic layer had the effect of reducing the nutrient supply from nutrients regenerated on the sediment/water interface. This in turn limited the productivity of the system and a large quantity of the standing crop became non-viable and sank into the anoxic layer. This process continued until equilibrium was achieved. A change in the pattern of stratification resulted in partial mixing of the water column in the December study and a higher standing crop was observed. By the time of the February survey, the pattern observed in the water column returned to the form of the May and September studies with a similarly high standing crop supported.

6.3 Sediment chemistry

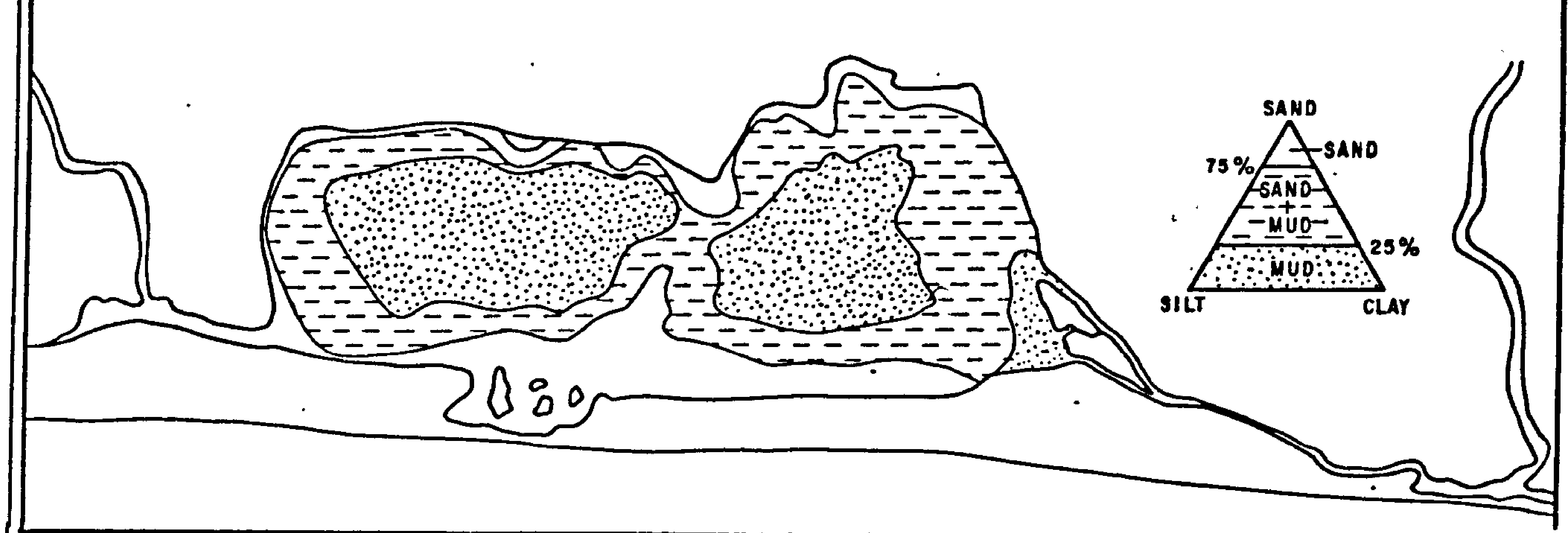
The classification of surface sediments in the Laguna Chautengo (Lankford *et al* 1975) is presented in fig. 6.19, together with the distributions of water content and of the percentage carbonate.

The distribution of surface sediments in the lagoon shows that the finest sediments are found in the central (deeper) part of the two basins forming the lagoon. The coarse grained sediments are found in the part of the lagoon adjacent to the sand barrier with a tongue of this sandy sediment extending inwards from the bar inlet. A region of fine sediments is located off the delta of the Rio Copala. The discharge of the Rio Nexpa is marked by an area of sandy sediments. This probably results from the fact that it has a higher flow rate (during the rainy season) than the Rio Copala which discharges through a number of smaller channels.

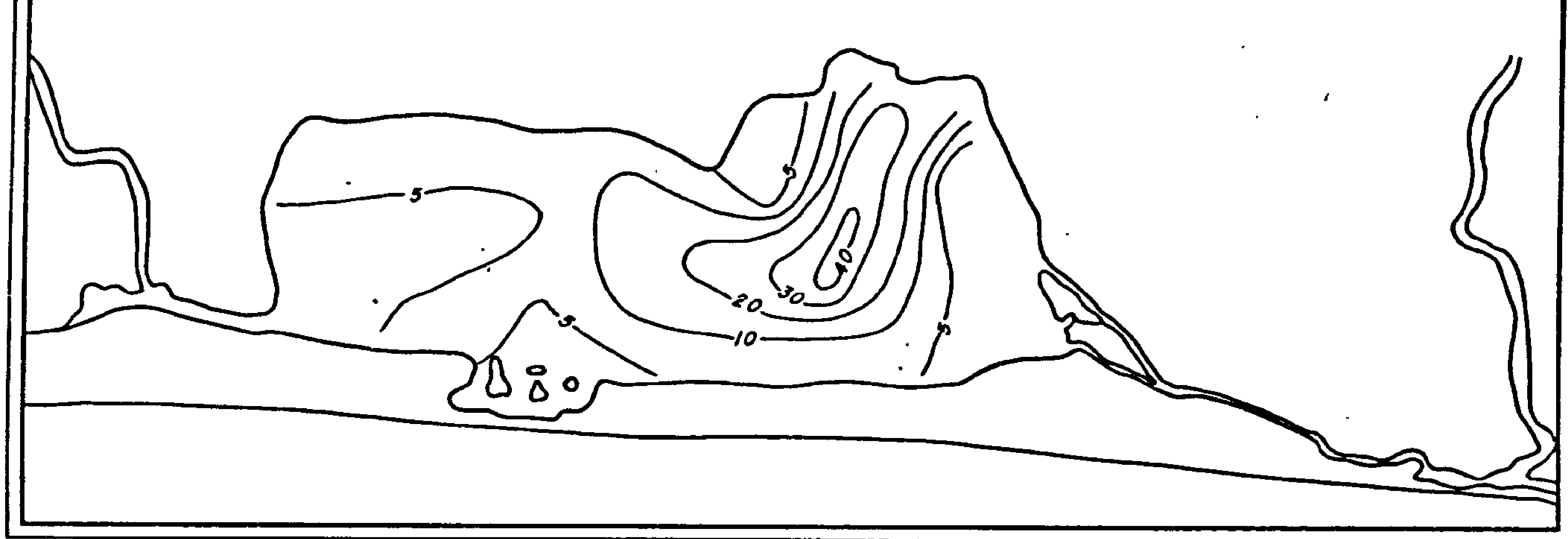
The distribution of percentage carbonate shows a large percentage of carbonate in the sediments of the eastern basin of the lagoon. This results from the extensive mussel beds (*Mytella strigata*) found in this part of the lagoon. It is possible that these beds have an important function in the chemistry of the lagoon since mussels have been shown to be capable of filtering very large quantities of phytoplankton, excreting much of the filtered material as organic detritus (Kuenzler 1961).

Figure 6.19
LAGUNA CHAUTENGO
GENERAL FEATURES OF SURFACE SEDIMENTS

GENERAL CLASSIFICATION (AFTER LANKFORD et al 1975 and 1976)



% CARBONATE (EXPRESSED AS % CALCIUM CARBONATE OF DRY WEIGHT)



LAGUNA DE CHAUTENGO GENERAL FEATURES OF SURFACE SEDIMENTS

The distribution of insoluble organic carbon and nitrogen and total phosphorus is shown in fig. 6.20. All three parameters show a similar distribution with highest concentrations towards the north and east of the lagoon. An area of particularly high nutrient concentrations may be observed from the discharge point of the Rio Copala. This may result from the long term deposition of detritus carried by the river from the adjacent mangrove areas. Almost no plume was associated with the faster-flowing Rio Nexpa. Within the lagoon higher sediment nutrient values appear to be associated with areas of finer sediments and in the deeper areas of the lagoon where there is very little resuspension of sediments by wave action.

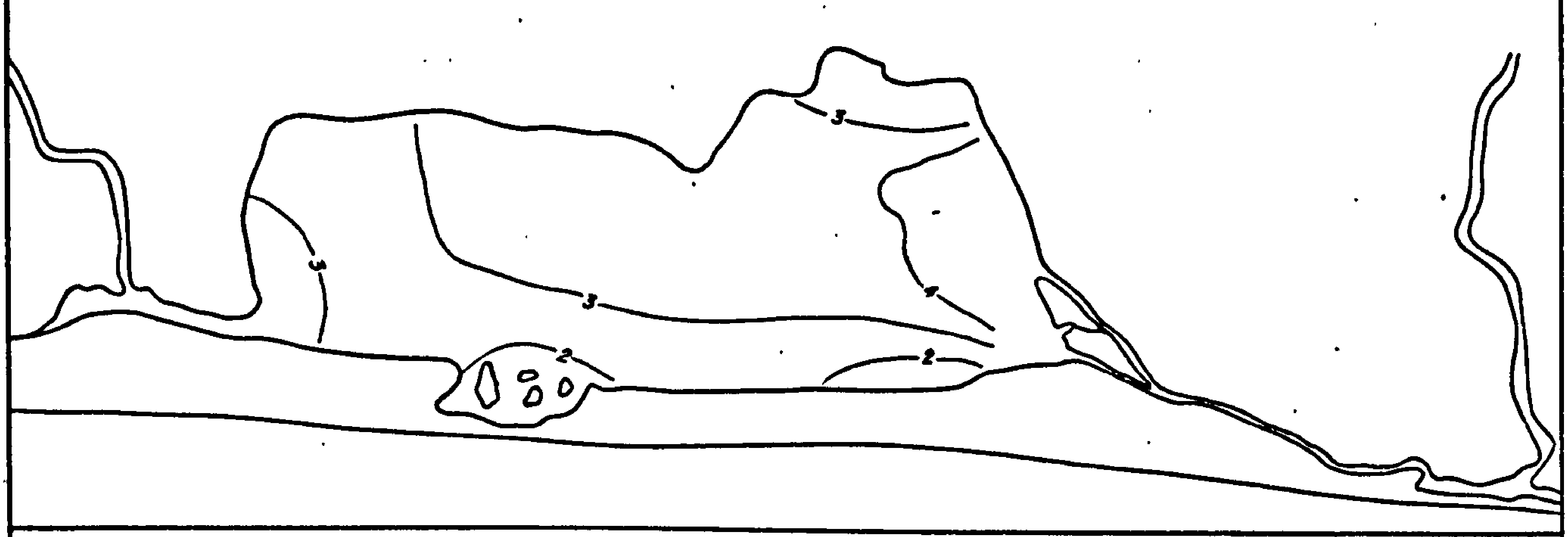
The input of detrital material to the lagoon, may have important consequences for its productivity. The gradual regeneration of nutrients from the detritus may provide an important source of nutrients to the lagoon. This regeneration, though continuing throughout the year should be particularly important during the dry season when there are limited external sources of nutrients to the lagoon. The gradual increase in the standing crop of phytoplankton observed during the period of isolation may result from this effect.

In order to examine variations in the nitrogen and carbon reservoirs in sediment cores and the phosphate and ammonia reservoir in interstitial waters, three 1 metre cores were obtained from the bottom sediments of Laguna Mitla.

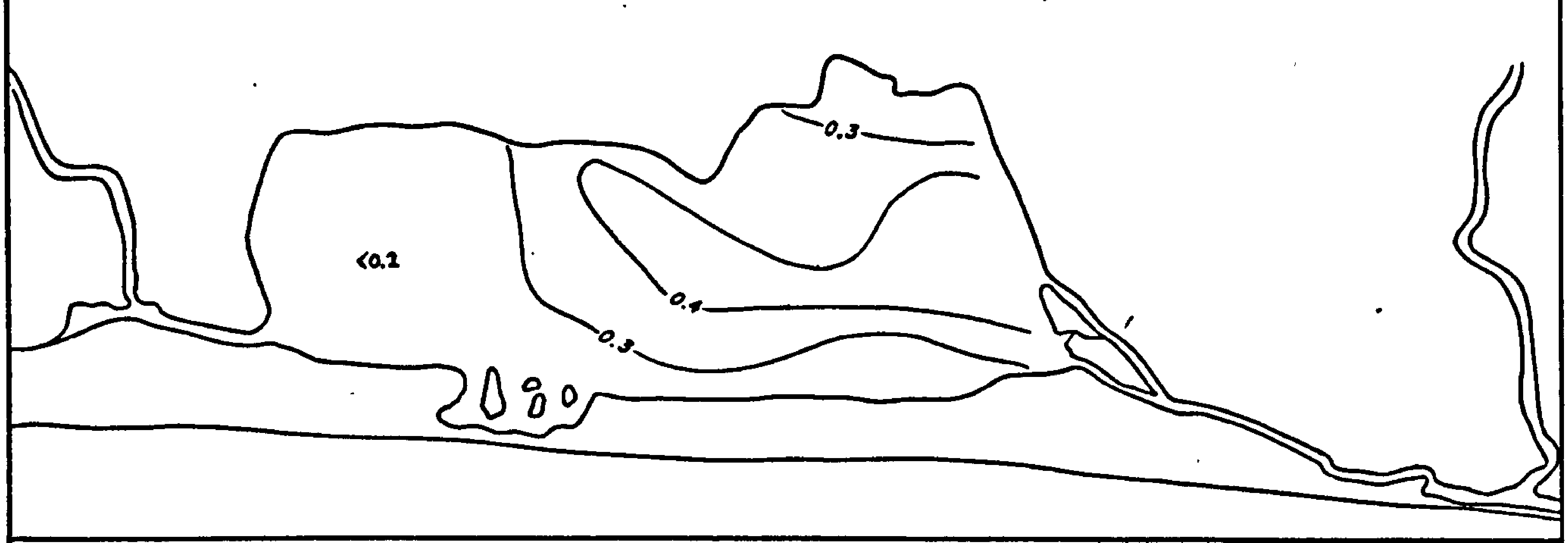
Core 1 was obtained in 3 metres of water at station 1 of Mitla, in the middle of the largest section of the lagoon. The first 35 cm of the core consisted of a brown, poorly consolidated

Figure 6.20
LAGUNA CHAUTENGO
SURFACE SEDIMENTS
CARBON, NITROGEN AND PHOSPHORUS

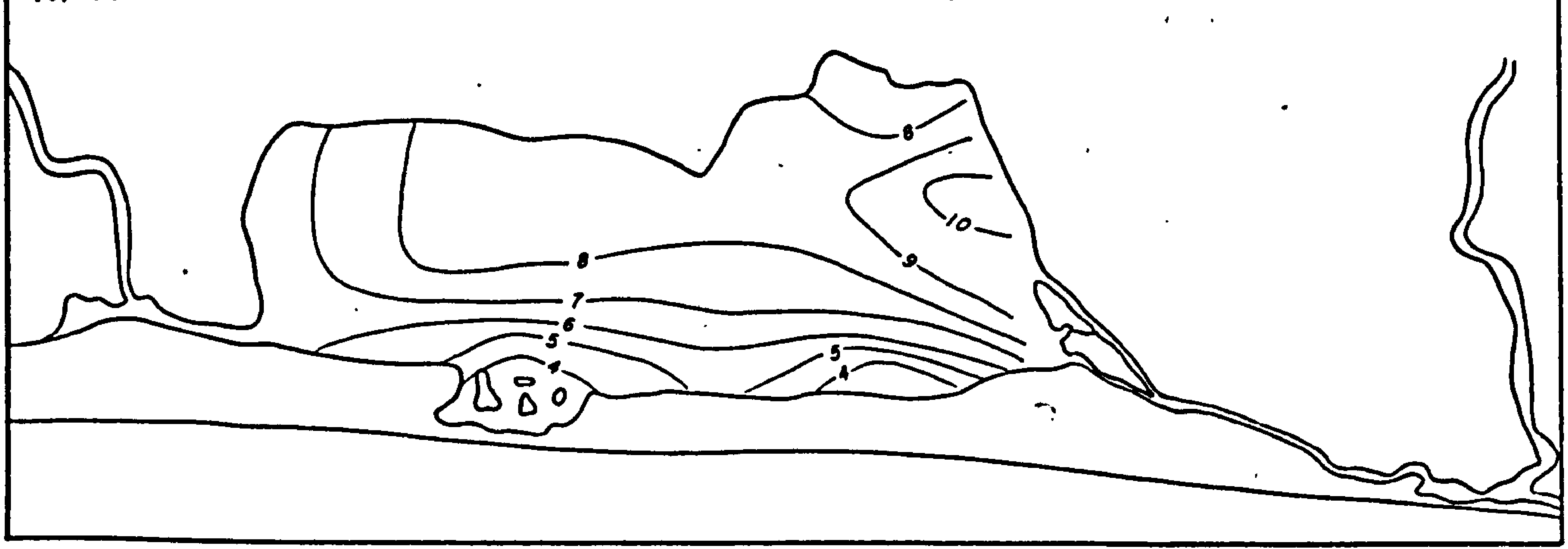
(a) % "ORGANIC CARBON" (NORMALISED TO TOTAL DRY WEIGHT)



(b) % "INSOLUBLE NITROGEN" (NORMALISED TO TOTAL DRY WEIGHT)



(c) TOTAL PHOSPHORUS - PARTS PER THOUSAND OF DRY WEIGHT)



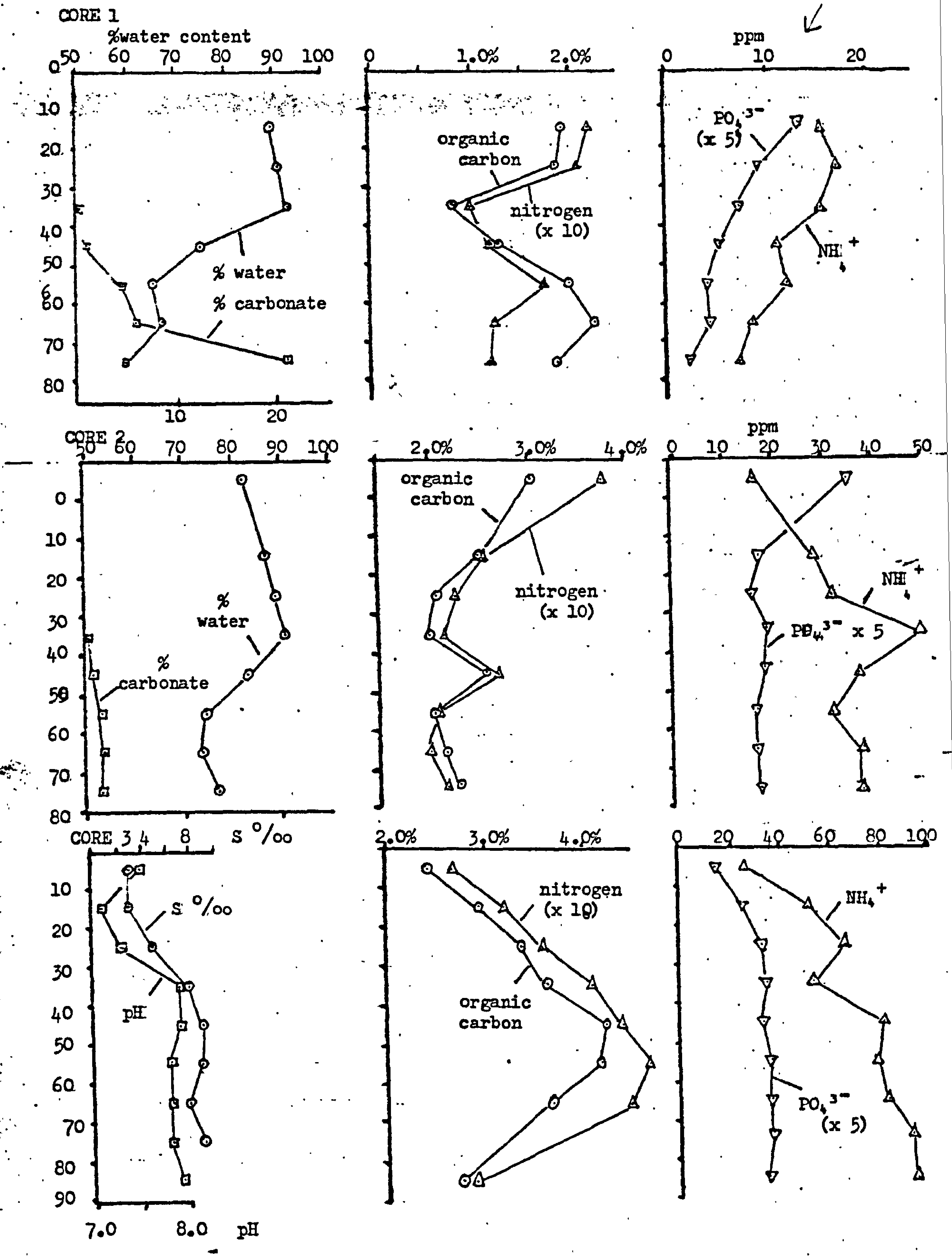
LAGUNA CHAUTENGO - SURFACE SEDIMENTS: CARBON, NITROGEN AND PHOSPHORUS sediment with a water content of about 90% (see fig. 6.21). Following a transition region of about 5 cm, 10 cms of a finer grey coloured material was encountered containing a few small shell fragments. The final section of the core consisted of a much coarser mud containing a large proportion of broken and complete mussel shells.

Core 2 was obtained in about 3½ metres of water at the entrance to the deeper "Camalote" basin (see fig. 3.3). The first 50 cms of the core consisted of the brown sediment described earlier and the remaining part was a grey colour with a very few shell fragments present. The final core (core 3) was obtained in 5½ metres of water in the "Camalote" basin and consisted entirely of the brown sediment of average water content 85%.

Figure 6.21 illustrates the chemical changes encountered in the cores. The different sediment types are reflected by the sharp changes in water content from the brown unconsolidated sediments to the grey and finally carbonate-rich sediments. The general level of carbon and nitrogen in the first 20 cms of each of the cores was similar (in core 2 it was a little higher than the other), reflecting the sedimentary conditions of the present time. The percentage carbon in the surface sediments was about 17% (dry weight) showing the high detrital content of the material sedimenting at present. Dissolved nutrient concentrations in the interstitial waters were very high, the concentration increasing from core 1 through core 2 to core 3. This shows the continuing regeneration from the detritus rich sediments.

Changes in the concentration of carbon and nitrogen within the cores illustrate the ecological changes within the

Figure 6.21
LAGUNA MITLA
RESULTS OF CORE ANALYSES


CORE 1
%water content
50 60 70 80 90 100
0 10 20 30 40 50 60 70 80
% water
% carbonate
10 20
0 1.0% 2.0%
organic carbon
nitrogen (x 10)
ppm
0 10 20
PO_4^{3-} (x 5)
NH_4^+
CORE 2
50 60 70 80 90 100
0 10 20 30 40 50 60 70 80
% water
% carbonate
2.0% 3.0% 4.0%
organic carbon
nitrogen (x 10)
ppm
0 10 20 30 40 50
NH_4^+
PO_4^{3-} x 5
CORE 3
4 8 S °/oo
10 20 30 40 50 60 70 80 90
S °/oo
pH
7.0 8.0 pH
2.0% 3.0% 4.0%
nitrogen (x 10)
organic carbon
0 20 40 60 80 100
NH_4^+
PO_4^{3-} (x 5)

lagoon. The high carbonate at the bottom of core 1 resulted from the growth of filter-feeding organisms and indicates a time when the water was well oxygenated and had a higher diversity of planktonic organisms. An increase in the carbon and nitrogen in the middle of core 3 may be the result of a time of even more intense eutrophication than at present. Since nitrogen is usually mobilised faster than carbon in aerobic conditions, variations in the carbon/nitrogen ratio may reflect major changes in the eutrophication of the lagoon. Values of this ratio are shown on table 6.4 for the cores under investigation.

Depth	Core 1 C/N	Core 2 C/N	Core 3 C/N
0 - 10	-	8.0	9.0
10 - 20	8.7	-	9.2
20 - 30	8.9	9.9	9.4
30 - 40	8.4	9.2	8.3
40 - 50	10.7	9.3	9.7
50 - 60	11.4	9.5	8.9
60 - 70	18.2	9.9	8.1
70 - 80	15.7	10.9	-
80 - 90	-	-	9.5

The increase in this ratio towards the bottom of core 1 suggests that nitrogen was lost from the sediments after deposition. Even in the well oxygenated conditions of the Laguna Chautengo this ratio rarely exceeded 10 for the surface sediments.

This implies that the C/N ratio of newly deposited detritus is generally below 10 in both lagoons. The ratios of above 15 at the bottom of core 1 thus show that the conditions of deposition and subsequent regeneration of Nitrogen permitted a net loss from the sediments at an earlier stage in the development of the lagoon. This process is comparable with the situation presently observed in Chautengo where removal of nutrients occurs during the period of communication of the lagoon with the sea. It is postulated that conditions within the Laguna Mitla were comparable with those presently found in Chautengo during the sedimentation which produced the lower part of Core 1.

7. Conclusions

The foregoing discussion illustrates how the tropical seasons influence the hydrography and consequently the chemistry of the lagoons studied. The morphology of the lagoons and the amount of run-off which they receive determines whether or not they communicate with the sea during the rainy season (June - November).

In the case of the two lagoons which open to the sea during this period, there develops a pattern of mixing and circulation which results in much of the dissolved and particulate material within the lagoon being carried out into the sea. At the same time, there appears to be a certain amount of detritus, originating from continental sources, mangrove areas, benthic plants and filter feeling animals, which is deposited on the lagoon floor. Following bar closure, nutrient recycling by the organisms within the lagoon, coupled with the gradual regeneration of nutrients from the deposited detritus maintains a higher standing crop than that encountered immediately before bar closure.

This nutrient recycling was found to be particularly important in the case of the isolated Laguna Mitla. The absence of communication with the sea had resulted in a gradual accumulation of nutrients in the lagoon, leading to the high standing crop of phytoplankton observed. This standing crop appears to be almost entirely maintained by nutrient regeneration. The large oxygen demand of the planktonic biomass, and of the bacterial flora of the associated detritus, lead to a water column in which the water layer adjacent to the sediments may become diurnally anoxic or, following seasonal stratification of the lagoon, completely anoxic.

During periods of diurnal anoxia, ammonia was produced in the anaerobic section of the water column. The net quantity of ammonia produced was of similar magnitude to the nitrogen equivalent of the net productivity. This suggests that the nutrients, bound within the detrital material falling from the water column, were recycled daily in order to maintain the steady standing crop. The occurrence of complete stratification inhibited the process of nutrient transport from the zone of regeneration. The consequent reduced nutrient supply supported a smaller, steady-state, standing crop.

If the Laguna Mitla is at a steady state, the annual supply of nutrients to the lagoon should be accompanied by an equivalent annual loss to the sediments. This is supported by the high content of carbon, nitrogen and phosphorus found in the sediments.

The effect of temporary isolation on the Laguna Apozahualco, which is shallower than the other two examples and does not receive a river discharge, is to produce very high salinities. The nutrients contained within the lagoon appear to become concentrated as the water volume is reduced by evaporation but the chlorophyll$_a$ (representing the suspended standing crop of phytoplankton) does not necessary mirror this concentration change. This results from the ecological changes caused by the stress of the hypersaline system, which alter the proportions of phytoplankton, invertebrates and blue-green algal mats in the system.

It was observed that eutrophication, in the coastal lagoons studied was limited by their degree of communication with the sea. In the Laguna Chautengo, the natural seasonal closure of the bar, coupled with fast nutrient regeneration, maintained a high productivity despite the limited input of nutrient material to the lagoon. It is proposed that, had the bar remained open, the productivity of the system would have decreased, due to the flushing of suspended particulate material from the lagoon. For Chautengo, the onset of the type of eutrophication found in Mitla, was observed in June following a large input of nutrients to the lagoon. The loss of suspended material to the sea following the opening of the bar in July, effectively prevented the eutrophication from further developing. An understanding of the processes involved in such eutrophication is essential before decisions concerning lagoon management (the control of the inputs and outflows of a lagoon in order to optimise its production) may be made.

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Table C1 - Chautengo Survey 16th January 1976

		Physical Properties			Alkalinity		Phosphorus		Pigments		Silicate
Station	Time	Depth m	Secchi Depth m	Salinity °/oo	pH	Total Alk.	Reactive	Total	CHL_a mg/m^3	Carot mg/m^3	
							µg at P.l^{-1}				µg at Si.l^{-1}
1	12.25	0.4	-	18.05	7.4	1.2	0.80	1.57	13.1	8.0	77.0
2	13.50	0.8	0.6	18.48	7.9	1.5	1.92	3.19	11.3	6.5	55.0
3	14.00	0.8	0.45	21.29	7.6	1.5	1.19	2.59	8.8	4.6	113.0
4	14.10	0.7	0.4	22.09	7.7	1.9	1.48	2.77	6.1	3.5	86.0
5	13.37	0.7	0.5	19.81	7.8	1.5	0.91	1.46	11.7	6.6	23.0
6	13.25	0.3	-	18.91	8.3	1.5	1.92	2.51	1.6	0.9	71.0
7	13.05	0.4	0.3	12.49	8.1	1.2	0.55	1.47	22.7	15.2	151.0
8	12.46	0.4	0.3	16.37	8.1	1.7	0.62	1.50	10.8	8.5	43.0
9	15.00	0.7	0.3	20.34	7.5	1.7	3.13	4.18	6.8	5.3	148.0
10	14.46	1.0	0.9	23.07	7.7	1.9	1.37	2.38	6.9	3.7	117.0
11	15.12	0.6	0.2	18.21	7.9	1.9	2.83	3.74	10.9	6.9	148.0
12	15.25	0.3	0.2	14.99	7.9	1.5	2.49	3.31	19.9	12.0	68.0
13	16.50	0.4	0.2	3.57	7.4	0.7	1.53	2.59	4.6	2.4	173.0
14	17.04	0.6	-	23.58	7.7	1.9	1.95	3.45	5.7	3.1	159.0
15	17.12	1.0	0.6	22.26	7.7	1.9	1.65	3.35	4.4	1.6	106.0
16	14.29	0.3	-	24.03	7.9	2.0	1.50	3.12	2.4	1.4	118.0
17	17.22	0.6	-	24.49	7.8	1.9	1.77	2.66	4.0	2.4	127.0
18	16.58	0.4	0.4	23.08	7.8	1.9	1.87	3.80	14.0	8.7	147.0
19	16.37	0.5	0.3	0.15	7.7	0.7	1.51	3.49	2.41	1.5	189.0

Table C2 - Chautengo Survey 2nd March 1976

	Physical Properties					Oxygen	Phosphorus		Pigments	
Station	Time	Depth	Secchi Depth	Temp.	Salinity		Reactive	Total	CHL_a	Carot
		m	m	°C	°/oo	p.p.m.	μg at $P.l^{-1}$		mg/m^3	mg/m^3
1	13.30	0.9	0.5	28.7	13.74	7.1	1.10	1.52	-	-
2	11.20	1.0	1.0	27.2	19.57	5.8	3.73	4.35	-	-
3	11.40	0.8	0.7	27.5	21.96	5.3	4.39	4.47	9.9	7.8
4	12.15	0.75	0.5	27.9	19.85	5.0	4.08	4.31	-	-
5	12.25	1.0	0.75	28.1	18.65	5.7	3.31	-	8.4	8.3
6	12.55	0.5	bottom	28.4	12.18	9.6	3.00	3.27	-	-
7	13.00	0.5	0.1	29.9	5.53	6.5	2.64	3.39	19.5	16.9
8	13.20	0.6	0.45	29.5	10.13	6.1	0.73	1.18	-	-
9	14.00	0.9	0.2	28.8	20.63	7.2	2.11	2.45	-	-
10	14.50	0.8	0.1	29.0	25.89	5.5	2.09	2.25	8.3	6.3
11	14.20	0.7	0.1	28.4	25.44	5.7	2.80	-	-	-
12	14.30	0.4	0.1	29.4	26.42	7.0	1.45	-	-	-
13	15.57	0.2	0.1	31.6	24.74	6.4	1.71	2.14	-	-
14	16.08	0.9	0.3	29.3	24.04	6.4	1.48	1.84	8.5	7.9
15	16.13	0.8	0.3	28.5	23.67	7.1	1.66	1.93	-	-
16	11.55	0.75	0.5	27.6	22.99	5.1	5.00	5.20	2.7	2.7
17	-	-	-	-	-	-	-	-	-	-
18	16.05	1.00	-	29.5	24.44	7.8	1.83	2.10	-	-
19	15.45	0.25	-	32.0	24.08	9.1	1.20	1.55	7.8	7.8

Table C3 - Chautengo Survey 4th April 1976

		Physical Properties				Oxygen	Phosphorus		Pigments		Silicate
Station	Time	Depth	Seochi Depth	Temp.	Salinity		Reactive	Total	CHL$_a$	Carot	
		m	m	°C	°/oo	p.p.m.	µg at P.l^{-1}		mg/m^3	mg/m^3	µg.at Sil^{-1}
1	17.01	0.5	0.2	31.2	16.16	6.0	0.96	1.86	18.7	15.9	95.0
2	17.23	1.4	0.2	31.2	20.16	6.0	1.51	3.72	20.3	20.9	76.0
3	17.44	1.2	-	31.2	23.03	-	1.41	2.74	17.8	13.7	52.0
4	15.15	0.7	0.3	31.2	24.02	7.0	1.00	1.82	1.4	-	-
5	15.35	1.3	0.2	31.5	21.88	7.6	1.46	2.46	27.7	20.2	90.0
6	16.04	0.75	0.4	32.2	22.47	8.1	1.26	2.33	11.4	9.3	39.0
7	16.25	0.5	0.1	32.2	13.73	6.4	1.84	2.58	12.4	13.4	34.0
8	16.47	0.7	0.1	32.2	14.64	6.5	0.67	1.67	19.4	18.2	77.0
9	07.40	0.7	0.4	26.2	26.06	4.6	3.00	4.23	18.7	11.5	92.0
10	07.20	0.6	0.3	26.8	26.54	4.1	1.91	3.00	23.3	16.0	65.0
11	07.05	0.4	0.3	26.0	25.84	4.6	2.04	3.19	8.0	7.5	57.0
12	06.40	0.6	0.2	25.2	25.96	4.6	2.24	3.57	10.8	10.4	41.0
13	09.55	0.2	0.2	28.0	25.41	4.5	1.53	2.40	3.9	3.3	62.0
14	10.20	0.6	0.4	-	24.70	-	1.98	3.46	3.2	-	67.0
15	10.35	0.7	0.6	29.0	24.62	5.8	1.82	3.02	9.7	8.6	68.0
16	-	-	-	-	-	-	-	-	-	-	-
17	10.55	1.7	bottom	28.2	25.21	4.8	1.70	2.72	-	-	50.3
18	10.10	0.4	0.3	28.9	25.26	6.3	1.61	2.73	7.6	4.8	-
19	09.35	0.3	0.3	27.5	25.49	5.8	1.63	2.71	13.4	9.0	40.0

Table C4 - Chautengo Survey 10th May 1976

		Physical Properties				Alkalinity		Phosphorus		Pigments		Inorganic Nitrogen			Silicate
Station	Time	Depth	Secchi Depth	Temp.	Salinity	pH.	Alk.	Reactive	Total	CHL$_a$	Carot	NH_4^+	NO_3^-	NO_2^-	
		m	m	°C	‰			µg at P.l^{-1}		mg m^{-3}	mg m^{-3}	µg at N.l^{-1}			µg. at Sil^{-1}
1	17.55	0.60	0.25	31.6	20.0	-	-	1.25	3.61	23.2	18.71	4.4	< 0.1	0.6	98.0
2	12.40	0.90	0.50	30.4	25.2	7.5	1.8	1.84	2.77	19.1	12.4	1.1	0.1	0.02	119.0
3	13.00	0.80	0.30	30.6	25.4	7.4	1.8	1.90	2.58	24.5	15.3	0.6	0.1	0.02	92.0
4	16.20	0.80	0.30	31.7	26.6	7.4	1.8	1.49	2.11	13.6	9.8	0.6	0.1	0.02	102.0
5	16.33	1.00	0.30	31.4	24.3	-	-	1.11	1.87	20.3	14.0	0.6	0.1	0.02	121.0
6	16.45	0.40	0.40	32.0	26.0	-	-	1.00	1.70	9.9	4.3	2.4	0.1	0.02	22.0
7	17.07	0.50	0.15	32.4	19.5	-	-	0.63	1.36	16.3	15.9	1.0	0.1	0.02	118.0
8	17.40	0.40	0.10	32.2	18.1	-	-	0.63	1.65	22.6	19.5	3.0	0.1	0.25	86.0
9	13.14	0.60	0.30	30.5	28.3	-	-	0.75	1.52	15.1	8.4	0.1	0.1	0.02	99.0
10	14.05	0.70	0.20	30.6	28.0	-	-	2.35	3.11	16.7	11.3	1.6	0.1	0.02	98.0
11	13.27	0.50	0.10	30.8	27.5	-	-	3.03	3.71	12.1	10.2	3.3	0.1	0.04	91.0
12	13.40	0.25	0.10	31.4	27.3	-	-	2.77	3.50	25.9	22.8	2.0	0.1	0.04	118.0
13	14.47	0.20	0.15	32.7	27.1	-	-	1.98	2.64	-	-	0.3	0.1	0.02	121.0
14	15.09	0.50	0.20	30.9	26.7	-	-	2.45	3.20	9.5	8.4	0.2	0.1	0.02	99.0
15	15.19	0.80	0.25	31.1	27.0	-	-	2.51	3.09	8.0	9.0	0.4	0.1	0.02	118.0
16	16.00	0.40	0.40	31.9	26.5	-	-	2.97	2.62	11.6	10.8	1.6	0.1	0.02	99.0
17	15.30	0.40	0.40	31.0	26.7	-	-	1.89	2.38	5.9	4.5	0.2	0.1	0.02	89.0
18	15.01	0.30	0.15	31.5	26.8	-	-	1.80	2.33	15.6	15.0	0.3	0.1	0.02	111.0

Table C5 - Chautengo Survey 16th June 1976

		Physical Properties				Alkalinity		Oxygen	Phosphorus		Pigments		Inorganic Nitrogen			Silicate
Station	Time	Depth	Secchi Depth	Temp.	Salinity	pH	Total Alk.		Reactive	Total	CHL$_a$.	Carot	NH$_4^+$	NO$_3^-$	NO$_2^-$	
		m	m	°C	‰			p.p.m	µg at P l^{-1}		mg/m^3	mg/m^3	µg at N.l^{-1}			µg at Sil^{-1}
1	16.25	1.6	0.80	34.0	11.4	8.1	0.9	8.0	0.80	1.40	12.6	12.8	0.2	0.05	0.02	80.0
2	10.46	1.7	0.60	32.4	12.6	7.7	0.9	10.4	2.07	4.87	55.0	32.3	1.7	0.05	0.02	87.0
3	11.12	1.6	0.65	31.8	11.1	8.1	1.2	12.6	1.97	4.50	70.3	40.5	2.2	0.22	0.21	111.0
4	15.32	1.5	0.70	32.6	11.7	8.6	0.9	11.7	1.78	3.45	53.0	43.4	0.6	0.05	0.02	108.0
5	15.42	2.0	0.60	32.8	12.1	8.5	0.9	13.2	1.70	3.73	54.9	39.1	0.5	0.05	0.02	74.0
6	15.52	1.3	0.60	32.4	11.7	8.4	0.9	13.3	1.19	1.89	42.8	35.5	0.1	0.1	0.02	77.0
7	16.02	1.2	0.70	32.2	9.2	8.4	0.9	12.3	1.13	1.76	21.5	21.7	0.1	0.05	0.02	131.0
8	16.12	1.6	0.60	33.4	10.4	8.6	1.2	11.6	1.02	1.73	21.7	18.6	0.6	0.05	0.02	118.0
9	11.27	1.5	0.50	32.3	10.8	8.1	0.9	10.3	2.26	4.64	121.5	63.6	1.5	9.15	0.85	126.0
10	12.28	1.7	0.75	32.0	9.1	8.2	0.9	15.0	1.68	3.13	109.2	57.9	1.1	0.05	0.14	134.0
11	11.44	1.5	0.60	32.0	9.0	7.6	1.2	9.8	2.31	4.74	55.7	31.2	12.4	10.1	1.3	127.0
12	12.08	1.3	0.60	32.4	8.5	8.1	1.2	14.3	1.50	2.31	53.5	38.2	0.3	0.05	0.02	134.0
13	13.29	1.0	0.50	32.9	7.5	7.6	0.7	13.4	1.45	2.34	84.0	47.1	0.1	0.05	0.02	195.0
14	13.44	1.4	0.80	32.4	8.7	8.2	1.2	14.5	1.56	2.86	69.3	53.0	0.1	0.05	0.02	144.0
15	13.52	1.4	0.60	32.4	8.9	8.3	0.9	15.6	1.52	2.88	82.0	54.7	0.1	0.05	0.02	139.0
16	15.23	1.5	1.10	32.5	10.3	8.4	-	14.6	1.76	3.46	42.8	34.3	0.1	0.05	0.02	134.0
17	15.05	2.1	1.30	31.6	11.4	8.1	1.2	12.2	1.84	3.57	62.1	35.4	0.2	0.33	0.12	124.0
18	13.37	1.2	0.70	32.6	8.3	8.2	0.9	13.9	1.34	2.47	88.8	53.0	0.6	0.05	0.02	144.0
19	13.05	1.0	0.40	32.2	2.3	7.2	0.5	9.2	1.93	3.72	32.0	16.5	0.6	0.05	0.12	151.0

Table C6 - Chautengo Survey 18th July 1976

Station	Time	Physical Properties				Alkalinity		Phosphorus		Pigments		Inorganic Nitrogen			Silicate
		Depth	Secchi Depth	Temp.	Salinity	pH.	Alk.	Reactive	Total	CHL_a	Carot	NH_4^+	NO_3^-	NO_2^-	
		m	m	°C	‰			µg at P. l^{-1}		mg/m^3	mg/m^3	µg at N. l^{-1}			µg at Sil^{-1}
1	-	1.10	0.80	33.1	15.0	7.5	1.5	1.42	2.50	15.00	12.96	0.3	0.05	0.02	29.0
2	10.01	1.30	bottom	31.5	16.1	7.6	1.2	1.39	2.31	6.23	6.16	0.5	0.05	0.02	65.0
3	09.48	1.50	bottom	30.0	17.9	7.6	1.5	1.45	2.57	2.46	2.24	0.5	0.05	0.02	65.0
4	09.35	1.20	bottom	29.6	19.0	7.7	1.2	1.30	2.36	1.22	1.92	0.4	0.05	0.02	64.0
5	10.12	1.50	bottom	30.8	16.0	7.6	1.2	1.33	3.50	5.17	3.90	0.4	0.05	0.02	11.0
6	-	1.00	bottom	31.7	12.0	7.3	0.7	1.21	1.97	11.8	10.31	0.3	0.05	0.02	74.0
6 (1.0m)	-	-	-	32.6	20.75	7.5	1.5	1.46	2.57	16.36	13.12	1.2	0.48	0.02	200.0
7	10.45	0.75	0.75	32.7	6.0	7.5	1.2	1.24	1.84	7.52	5.40	1.1	0.43	0.1	89.0
8	10.53	1.00	0.80	32.6	11.0	7.3	0.5	1.40	2.24	10.03	8.40	0.5	0.05	0.02	32.0
9	07.50	1.00	bottom	30.7	23.0	7.85	1.9	1.56	3.04	13.8	11.70	0.6	0.05	0.02	53.0
10	08.00	1.20	bottom	30.0	22.0	7.95	1.8	1.57	3.04	5.65	5.86	0.8	0.05	0.02	52.0
11	07.35	0.95	bottom	30.8	22.0	7.85	2.0	1.24	1.76	-	-	0.5	0.05	0.02	37.0
12	07.18	0.60	bottom	30.0	14.5	8.2	1.7	1.81	3.82	72.3	57.4	0.3	0.05	0.02	117.0
13	07.00	0.50	0.20	29.4	0.0	7.1	0.4	1.94	4.09	18.69	13.4	5.9	1.0	0.30	68.0
14	06.44	0.90	0.20	29.3	2.0	7.4	2.3	1.69	3.34	8.99	5.50	5.7	10.9	0.14	87.0
15	06.31	1.10	0.40	28.7	6.5	7.3	-	1.73	3.50	6.20	4.00	20.0	5.2	0.20	15.0
16	09.26	0.75	bottom	30.6	33.45	7.9	2.3	1.06	1.51	2.2	1.88	0.1	0.05	0.02	3.0
17	06.17	1.50	0.50	29.2	15.5	7.7	1.6	1.55	2.96	4.06	4.10	1.0	2.0	0.08	68.2
18	06.48	0.85	0.30	29.3	1.5	7.3	0.6	1.66	3.55	10.40	6.20	6.2	4.95	0.16	212.2
18(0.5m)	-	-	-	30.0	19.0	7.6	1.7	1.67	3.30	7.7	7.50	6.7	1.16	0.14	24.2
19	07.10	0.50	0.20	29.3	0.00	7.5	0.2	2.25	4.18	7.54	4.70	1.5	15.2	1.4	212.2

Table C7 - Chautengo Survey 13th September, 1976

		Physical Properties					Oxygen	Phosphorus		Pigments		Silicate
Station	Time	Depth	Secchi Depth	Temp.	Salinity	pH		Reactive	Total	CHL_a	Carot	
		m	m	°C	°/oo		p.p.m.	µg at l^{-1}		mg/m^3	mg/m^3	µg at Sil^{-1}
1	-	1.33	0.2	32.8	10.1	-	-	1.72	2.15	7.48	7.12	194.0
2	18.40	1.50	0.3	31.7	12.2	-	7.5	1.33	1.66	11.68	9.04	124.0
3	17.19	1.60	bottom	31.7	15.5	7.9	7.9	1.53	1.93	4.87	6.36	141.0
4	16.35	0.80	bottom	31.7	14.6	7.8	7.8	1.65	2.06	6.29	5.68	189.0
5	17.36	1.50	0.3	31.8	12.4	-	6.4	1.75	2.13	7.46	6.92	174.0
6	17.50	0.75	0.2	32.0	11.6	7.0	6.8	1.69	2.04	8.05	7.56	208.0
7	18.11	0.85	0.25	31.6	1.2	-	6.3	1.13	1.45	9.15	7.92	36.0
8	-	-	-	-	-	-	-	-	-	-	-	-
9	14.00	1.00	0.40	33.7	13.7	7.0	8.0	-	2.13	11.58	9.56	154.0
10	14.16	1.30	bottom	33.1	15.9	7.8	8.0	1.93	2.28	9.21	7.76	143.0
11	14.41	0.90	0.30	34.0	15.9	7.2	7.2	2.17	2.54	14.30	13.12	130.0
12	14.52	0.90	0.20	33.5	14.5	7.9	8.4	1.95	2.37	20.63	19.0	166.0
13	15.29	0.50	0.40	33.0	1 .5	7.5	-	2.06	2.33	16.14	10.56	202.0
14	15.45	1.10	bottom	32.0	17.0	7.9	-	2.16	2.27	9.53	8.94	163.0
15	15.53	1.0	bottom	32.0	14.4	7.8	7.8	2.01	2.00	2.57	2.56	216.0
16	16.20	0.40	bottom	30.3	33.2	7.8	7.3	0.98	1.32	1.31	1.4	9.4
17	16.01	1.90	bottom	32.1	17.1	7.7	7.7	1.52	1.82	3.55	3.88	155.0
18	15.36	0.90	0.50	32.2	20.0	7.6	8.6	1.83	2.15	15.77	17.52	207.0
19	15.22	0.50	0.40	33.7	0.0	7.8	8.7	2.26	2.60	15.58	8.84	245.0

Table C8 - Chautengo Survey 1st and 2nd November 1976

		Physical Properties				Phosphorus		Pigments		Inorganic Nitrogen			Silicate
Station	Time	Depth	Secchi Depth	Temp.	Salinity	Reactive	Total	CHL_a	Carot	NH_4^+	NO_3^-	NO_2^-	
		m	m	°C	‰	µg at $P.l^{-1}$		mg/m^3	mg/m^3	µg at $N.l^{-1}$			µg at $Si l^{-1}$
1	14.15	1.02	0.75	34.2	3.8	0.55	1.10	7.73	7.31	1.3	0.1	0.05	118.0
2	14.30	1.19	1.0	33.5	6.2	0.90	1.52	4.90	5.50	0.8	0.1	0.05	39.0
3	14.50	1.29	1.0	32.6	8.3	0.73	1.23	3.95	4.20	0.4	0.1	0.05	145.0
4	18.25	1.00	bottom	31.4	15.7	0.92	1.57	2.63	3.30	0.5	0.1	0.05	90.0
5	14.30	1.30	bottom	32.4	5.8	0.66	1.30	4.81	3.81	0.6	0.1	0.05	94.0
6	14.40	0.60	bottom	32.2	7.8	0.88	1.58	4.72	4.96	0.8	0.1	0.05	45.0
7	14.50	0.75	bottom	32.2	0.8	-	-	3.60	4.09	0.3	0.1	0.05	58.0
8	15.00	0.77	0.70	32.8	2.3	0.77	1.32	4.96	5.37	0.7	0.1	0.05	51.0
9	15.00	0.95	bottom	33.0	9.5	0.80	1.48	5.65	6.46	0.4	0.1	0.05	-
10	15.15	1.16	bottom	32.4	14.4	1.50	2.14	4.17	4.31	0.3	0.1	0.05	142.0
11	15.30	0.91	bottom	33.3	11.3	1.63	2.20	3.62	4.13	0.4	0.1	0.05	217.0
12	15.50	0.73	bottom	34.0	7.4	2.00	2.60	4.29	3.71	0.5	0.1	0.05	223.0
13	16.30	0.62	0.42	32.7	0.0	2.41	2.95	6.19	3.97	1.0	0.7	0.12	-
14	16.47	0.83	0.80	32.8	14.0	1.65	2.32	4.09	4.45	0.6	0.1	0.05	216.0
15	16.55	1.18	1.10	32.5	19.0	1.75	2.35	1.86	2.45	0.6	0.1	0.05	109.0
16	18.15	0.69	bottom	31.8	15.6	1.30	1.83	1.52	3.00	0.4	0.1	0.05	140.0
17	17.15	1.0	bottom	32.6	17.4	1.55	2.09	3.08	2.95	0.4	0.1	0.05	104.0
18	16.40	0.89	0.40	32.9	7.6	1.90	2.42	6.22	5.51	0.7	0.1	0.05	193.0
19	16.20	0.68	0.50	32.7	0.0	2.43	2.93	1.66	1.53	1.0	1.1	0.14	-

Table C9 - Chautengo Survey 9th December 1976

		Physical Properties					Oxygen	Phosphorus		Pigments		Inorganic Nitrogen			Silicate
Station	Time	Depth	Secchi Depth	Temp.	Salinity	pH	p.p.m.	Reactive	Total	CHL_a	Carot	NH_4^+	NO_3^-	NO_2^-	
		m	m	°C	°/oo			µg at $P.l^{-1}$		mg/m^3	mg/m^3	µg at $N.l^{-1}$			µg at Sil^{-1}
1	17.50	0.90	0.30	31.0	16.5	7.5	8.2	0.84	1.89	4.84	-	0.1	0.07	0.08	63.0
2	11.30	1.40	bottom	30.1	18.6	7.75	7.1	1.07	1.76	-	-	0.1	0.20	0.02	177.0
3	12.04	1.20	bottom	29.7	14.5	7.4	6.5	0.84	1.59	1.22	0.91	0.1	0.05	0.02	33.0
4	16.44	0.90	bottom	30.5	21.7	8.1	8.3	1.99	2.44	5.67	-	0.1	0.05	0.02	114.0
5	16.55	1.50	bottom	30.4	13.8	7.9	9.1	1.33	1.89	9.17	5.29	0.3	0.05	0.08	54.0
6	17.09	0.60	bottom	31.0	16.5	7.6	6.1	1.68	2.43	-	-	0.3	0.05	0.08	61.0
7	17.21	0.60	bottom	31.0	1.4	7.2	7.3	0.77	1.23	1.62	1.19	0.7	0.33	0.02	45.0
8	17.34	1.00	bottom	31.1	11.0	7.5	8.6	0.88	1.40	1.73	1.12	0.1	0.05	0.03	116.0
9	12.26	1.10	bottom	30.2	23.0	7.9	6.5	1.53	2.14	3.93	2.17	0.1	0.05	0.03	83.0
10	13.09	1.00	bottom	31.3	20.2	8.0	6.6	1.27	2.03	1.95	-	0.1	0.2	0.21	80.0
11	12.40	1.00	bottom	30.0	23.0	8.0	8.3	1.67	2.48	2.25	2.04	0.1	0.1	0.02	114.0
12	12.54	0.60	bottom	30.6	21.0	8.2	9.3	3.30	3.97	7.10	3.84	0.9	0.05	0.02	136.0
13	14.01	0.40	bottom	30.8	0.3	7.8	8.4	2.01	2.32	-	-	1.0	1.3	0.08	230.0
14	14.19	1.00	bottom	30.6	24.2	7.8	8.0	1.34	1.91	1.60	1.47	0.1	0.6	0.08	132.0
15	14.30	0.80	bottom	30.2	23.5	7.9	7.6	1.43	1.89	1.00	1.12	0.1	0.53	0.03	104.0
16	14.55	0.55	bottom	30.6	22.8	8.1	9.3	1.29	1.93	3.27	2.17	0.1	0.05	0.02	135.0
17	14.45	1.40	bottom	30.8	18.8	7.9	9.3	1.36	1.92	1.0	0.91	0.9	0.46	0.02	104.0
18	14.12	0.60	bottom	31.4	19.4	7.4	8.2	1.80	2.10	1.55	-	0.1	1.95	0.05	173.0
19	13.35	0.40	bottom	30.3	0.0	8.1	8.0	2.17	2.54	1.17	0.63	0.6	1.3	0.09	300

Table C10 - Salinity and Temperature profiles in the 18th July Chautengo Survey

Station	Depth m	Depth of observation m	Temp. °C	Salinity ‰
1	1.1	S	33.1	15.0
		0.5	32.7	15.0
		1.0	33.0	14.6
		Integrated		14.9
2	1.3	S	31.5	16.1
	(0.95)	1.0	33.8	27.0
		Integrated		18.6
3	1.5	S	30.0	17.9
	(0.95)	1.0	33.0	29.0
		Integrated		21.6
4	1.2	All	29.6	19.0
5	1.5	S	30.8	16.0
	(0.95)	1.0	33.4	25.8
		Integrated		19.3
6	1.0	S	31.7	12.0
		0.5	31.0	13.75
		1.0	32.6	20.75
		Integrated		15.1
7	0.75	S	32.7	6.0
		0.5	32.6	14.5
		Integrated		12.5
8	1.0	S	32.6	11.0
		0.5	32.7	15.5
		Integrated		15.5

Station	Depth m	Depth of observation m	Temp. °C	Salinity ‰
9	1.0	All	30.7	23.0
10	1.2	All	30.0	22.0
11	0.95	All	30.8	22.0
12	0.6	S	30.0	14.5
		0.5	31.4	17.0
		Integrated		16.0
13	0.5	S	29.4	0.00
		0.5	31.4	18.9
		Integrated		5.7
14	0.9	S	29.3	2.0
	(0.3)	0.5	-	18.0
		Integrated		11.6
15	1.1	S	28.7	6.5
	(0.15)	0.5	-	29.0
		1.0	-	31.0
		Integrated		22.8
16	0.75	All	30.6	33.45
17 08.50 hrs	1.5	All	30.2	33.45
18	0.85	S	29.3	1.5
		0.5	30.0	19.0
		Integrated		12.8
19	0.5	All	29.3	0.0

Note - Figures in parenthesis indicate the extension of the upper mixed layer.

Table C11 - Salinity and Temperature profiles in the 13th September Chautengo Survey

Station	Depth m	Measurement Depth m	Temp. °C	Salinity ‰	Integrated Salinity ‰
1	1.33	All	32.8	10.1	10.1
2	1.50	All	31.7	12.2	12.2
3	1.6	S	31.7	15.5	15.9
		0.5	32.2	15.5	
		1.4	32.7	16.5	
4	0.8	S	31.7	14.6	15.6
		0.25	32.2	14.7	
		0.50	32.2	15.5	
		0.75	32.7	18.3	
5	1.5	All	31.8	12.4	12.4
6	0.75	All	32.0	11.6	11.6
7	0.85	All	31.6	1.2	1.2
9	1.00	All	33.7	13.7	13.7
10	1.30	S	33.1	15.9	18.7
		0.5	33.2	15.9	
		1.0	33.9	22.5	
11	0.90	All	34.0	15.9	15.9
12	0.90	S	33.5	14.5	14.5
		0.5	34.1	14.5	
13	0.50	S	33.0	1.5	17.7
		0.25	-	28.5	
14	1.10	S	32.0	17.0	28.8
		0.25	32.5	26.5	
		0.50	32.1	31.4	
		0.75	32.0	31.8	
		1.00	32.0	31.8	
15	1.0	S	32.0	14.4	20.9
		0.25	32.8	14.9	
		0.50	32.9	16.0	
		0.75	32.5	29.4	
		0.95	31.5	32.0	
16	0.4	All	30.3	33.3	33.3
17	1.9	S	32.1	17.1	26.6
		0.25	32.3	18.4	
		0.50	32.3	22.4	
17		0.75	32.3	25.5	
		1.00	32.4	28.0	
		1.50	31.3	32.2	
		1.90	30.8	33.4	
18	0.9	S	32.2	20.0	26.7
		0.25	32.5	23.6	
		0.5	32.1	31.6	
		0.75	-	32.0	
19	0.5	All	33.7	0.0	0.0
Bar Inlet	2.4	S	30.2	17.9	
		0.25	30.5	33.5	

Table C12 - Salinity and Temperature profiles in the 1st and 2nd November Chautengo Survey

Station	Depth m	Measurement Depth m	Temp °C	Salinity °/oo	Integrated Salinity °/oo
1	1.02	S	34.2	3.8	4.2
		1.0	33.5	4.6	
2	1.19	S	33.5	6.2	9.2
		0.5	33.6	6.2	
		1.0	33.8	13.7	
3	1.29	S	32.6	8.3	17.7
	(0.65)	0.5	32.9	8.3	
		1.0	33.2	27.3	
4	1.00	S	31.4	15.7	16.1
		0.5	-	15.4	
		1.0	-	17.2	
5	1.30	S	32.4	5.8	9.2
	(0.85)	0.5	32.4	5.8	
		0.75	32.2	6.3	
		1.0	33.2	15.2	
		1.25	33.3	17.5	
6	0.60	S	32.2	7.8	9.15
		0.5	32.2	10.5	
7	0.75	S	32.2	0.8	1.9
		0.5	32.2	3.0	
8	0.77	All	32.8	2.3	2.3
9	0.95	All	33.0	9.5	9.5
10	1.16	S	32.4	14.4	17.2
	(0.90)	0.5	33.0	14.5	
		1.0	33.4	26.5	
11	0.91	S	33.3	11.3	11.7
		0.5	33.6	12.1	
12	0.73	S	34.0	7.4	7.5
		0.5	34.2	7.5	
13	0.89	S	33.0	0	0.66
		0.5	33.1	1.5	0.66
14	0.83	S	32.8	14	22.0
		0.25	32.8	21.8	
		0.5	32.9	22.4	
		0.75	33.0	26.5	
15	1.18	S	32.5	19.0	19.9
		0.5	32.8	17.5	
		1.0	32.5	23.1	
16	0.69	S	31.8	15.6	16.1
		0.5	32.4	16.3	
17	1.0	S	32.6	17.4	20.3
		0.5	32.6	21.6	
		0.9	32.6	22.0	
18	0.89	S	32.9	7.6	18.8
		0.25	-	19.4	
		0.5	32.6	24.1	
19	0.68	All	32.7	0.0	0.0

Note - Figures in parenthesis indicate the extension of the upper mixed layer.

Table C13 - Salinity and Temperature profiles in the 9th December Chautengo Survey

Station	Depth	Measurement Depth	Temp	Salinity	Integrated Salinity
	m	m	°C	°/oo	°/oo
1	0.90	All	31.0	16.5	16.5
2	1.40	S	30.1	18.6	20.4
		0.5	30.0	18.8	
		1.0	29.9	22.3	
3	1.20	S	29.7	14.5	20.2
		0.5	29.6	19.0	
		1.0	30.1	24.7	
4	0.90	S	30.5	21.7	23.3
		0.5	30.6	23.9	
5	1.5	S	30.4	13.8	17.4
		0.5	30.6	13.8	
		1.0	30.8	21.0	
6	0.6	S	31.0	16.5	16.5
		0.5	31.2	16.5	
7	0.6	S	31.0	1.4	5.0
		0.5	32.5	8.5	
8	1	S	31.1	11.0	11.0
		0.5	31.2	11.0	
9	1.10	S	30.2	23.0	23.0
		0.5	30.2	23.0	
		1.0	30.2	22.5	
10	1.0	S	31.3	20.2	23.7
		0.5	31.3	22.8	
		1.0	30.8	29.0	
11	1.0	S	30.0	23.0	23.3
		0.5	30.0	23.0	
		1.0	30.1	24.2	
12	0.6	S	30.6	21.0	21.0
		0.5	30.6	21.0	
13	0.4	S	30.8	0.3	0.3
14	1.0	S	30.6	24.2	27.4
		0.5	30.3	27.0	
		0.75	30.8	31.5	
15	0.8	S	30.2	23.5	26.2
		0.5	30.4	30.7	
16	0.55	S	30.6	22.8	25.3
		0.5	30.6	27.8	
17	1.40	S	30.8	18.8	24.4
		0.5	30.2	25.0	
		1.0	29.9	26.3	
18	0.60	S	31.4	19.4	24.0
		0.5	31.4	28.5	
19	0.40	All	30.3	0	0.0

Table C14 - 24 hour Station, Chautengo Station 3, 5th April, 1976

	Physical Properties					Oxygen	Dissolved Phosphorus ug at P l^{-1}		NH_4^+	Silicate
Time	Temperature °C Air	Temperature °C Water	Relative Humidity %	Wind Velocity m/s	Salinity ‰	p.p.m	Reactive	Total	ug at N l^{-1}	ug at Sil^{-1}
14.15	29.4	30.8	78	S. 10-12	20.2	10.0	1.5	2.8	3.4	93.
17.45	27.2	31.2	82	S 5	22.0	8.6	1.4	2.9	0.21	52.
20.25	26.7	29.7	87	W 3-4	20.2	7.1	1.9	3.1	2.7	70.
23.46	25.0	29.4	93	var.W 1	21.0	5.4	1.7	8.0	2.0	62.
02.50	23.9	26.7	92	-	22.0	5.1	1.7	2.8	7.2	41.
05.30	21.7	26.7	94	1	13.0 (?)	4.3	1.7	2.7	4.3	41.
08.35	25.8	27.2	87	1	20.0	5.1	1.6	2.4	0.8	68.
12.15	31.1	30.5	74	S 6	21.0	12.0	1.5	2.5	1.2	67.

Table C15 - 24 hour Station 10th December, 1976 (Depth 1.3m) Station 3 Laguna Chautengo

Time	Observation Depth m	Salinity ‰	Integrated Salinity ‰	Temp. °C	Oxygen p.p.m	T Time	Observation Depth m	Salinity ‰	Integrated Salinity ‰	Temp. °C	Oxygen p.p.m
11.10	S	17.0	21.0	28.8	6.8	22.00	S	17.4	22.4	29.6	7.5
	0.5	19.1		28.6	6.7		0.5	18.2		29.9	7.0
	1.0	24.5		29.6	4.8		1.0	28.4		30.6	5.6
13.25	S	15.5	22.3	29.9	7.9	24.15	S	17.6	22.3	29.7	6.0
	0.5	24.5		30.8	7.8		0.5	17.8		29.7	6.0
	1.0	23.4		30.8	5.8		1.0	28.4		30.4	6.5
14.55	S	15.5	19.35	30.5	-	02.30	S	17.0	22.5	29.2	6.7
	0.5	15.6		30.5	-		0.5	18.6		29.7	6.7
	1.0	24.5		31.6	-		1.0	28.5		30.2	5.0
15.45	S	15.9	16.1	30.7	8.0	04.30	S	17.4	22.5	28.6	-
	0.5	16.0		30.8	8.0		0.5	18.4		29.0	-
	1.0	16.2		31.9	5.6		1.0	28.6		30.0	-
18.12	S	16.4	19.6	30.3	7.8	06.45	S	18.0	22.7	27.9	6.2
	0.5	16.4		30.4	7.8		0.5	18.0		27.7	6.1
	1.0	23.9		31.3	6.2		1.0	29.2		29.8	3.2
20.20	S	16.5	22.0	30.2	7.6	08.50	S	18.6	22.1	27.4	6.6
	0.5	20.4		30.9	6.8		0.5	18.5		27.4	6.4
	1.0	25.9		31.1	6.0		1.0	26.9		29.4	4.6

Table C16 - Salinity measurements during 24-hour stations in the bar channel - Laguna Chautengo

1 December 1975		17 January 1976		14 September 1976	
Time	Salinity °/oo	Time	Salinity °/oo	Time (Depth)	Salinity °/oo
		15.00	25.50	11.10 (S)	25.3
11.50	15.44	17.30	24.80	(0.5m)	27.0
14.30	16.98	19.00	23.29	13.10 (S)	23.0
16.50	18.76	21.00	23.52	(0.5m)	23.0
19.20	19.17	23.00	23.58	14.25 (S)	21.6
20.30	19.62	01.15	27.03	(0.5m)	22.5
22.05	19.75	03.00	28.46	16.35 (S)	25.9
24.00	33.74	05.00	31.14	(0.5m)	21.8
02.50	34.00	07.30	22.99	21.30 (S)	14.5
05.45	33.97	09.15	21.64	23.20 (S)	11.4
07.20	27.26	11.00	22.21	01.30 (S)	24.1
09.15	15.23	13.00	23.61	03.50 (S)	22.5
				06.00 (S)	29.0

Table A.1 - Apozahualco Survey 29th November, 1975

Station	Depth m	Secchi Depth m	Salinity °/oo	Reactive Phosphate µg at P l^{-1}	Total Dissolved Phosphorus µg at P l^{-1}	Chlorophyll$_a$ mg m^{-3}
1	1.0	-	29.39	1.76	2.4	-
2	-	-	-	-	-	-
3	0.5	-	29.53	2.1	2.6	-
4	1.0	1.0	29.50	2.0	2.5	5.9
5	-	-	-	-	-	-
6	0.7	0.35	28.77	2.15	2.75	-
7	0.4	-	29.67	3.2	-	-
8	0.7	0.30	29.79	3.6	4.3	-

Table A. 2 - Apozahualco Survey 15th January, 1976

Station	Depth m	Secchi Depth m	Salinity °/oo	Reactive Phosphate µg at P l^{-1}	Total Dissolved Phosphorus µg at P l^{-1}	Chlorophyll$_a$ mg m^{-3}
1	1.5	1.0	40.10	3.4	3.9	7.9
2	0.5	-	40.68	1.35	2.7	19.0
3	0.8	-	40.48	2.7	5.25	7.8
4	0.6	-	40.17	-	1.5	4.5
5	0.7	-	40.17	3.8	5.0	8.9
6	0.4	-	40.20	3.4	5.1	8.1
7	0.25	-	40.96	3.9	5.6	6.8
8	0.25	-	42.94	4.3	3.8	22.1

Table A.3 - Apozahualco Survey 29th February, 1976

Station	Time	Temperature $^{\circ}C$	Salinity $^{\circ}/_{oo}$	Oxygen p.p.m.	Chlorophyll$_a$ mg m^{-3}
1	17.15	29.7	55.70	6.5	7.3
3	17.35	29.8	61.17	5.0	19.2
4	17.57	29.8	61.81	6.5	31.6
5	18.25	28.8	59.23	6.2	19.7
7	18.40	28.9	59.87	6.7	21.1
Sea	17.00	-	34.95	-	1.8

Table A.4 - Apozahualco Survey 6th April, 1976

Station	Temperature $^{\circ}C$	Salinity $^{\circ}/_{oo}$	Reactive Phosphate µg at P l^{-1}	Total Dissolved Phosphorus µg at P l^{-1}	Chlorophyll mg m^{-3}
1	32.8	74.7	4.54	7.35	67.7
3	-	79.5	6.46	9.05	-
4	-	82.2	2.44	5.25	87.8
5	-	88.5	1.76	4.05	-
7	-	104.4	3.08	6.10	72.7

Table A.5 - Apozahualco Survey 9th May, 1976

Station	Temperature $^{\circ}C$	Salinity $^{\circ}/_{oo}$	Reactive Phosphate µg at P l^{-1}	Chlorophyll$_a$ mg m^{-3}
1	33.0	103	4.33	-
4	-	124	4.71	17.8
5	-	127	4.11	-
extra	-	-	4.68	-

Table A.6 - Apozahualco Survey 15th June 1976

Station	Time	Depth	Temp.	Salinity	pH	Reactive Phosphate	Total Dissolved Phosphorus	CHLOROPHYLL
		m	°C	‰		µg at P l^{-1}		mg/m^3
1 (s)	11.15	2.0	31.8	14.7	9.0	0.87	1.7	46.0
(0.5m)			33.8	28.5				
(1.0m)			37.0	-				
(1.3m)			40.5	95.0	7.5	21.9	66.0	
2	11.58	0.5	33.0	14.2	8.7	0.81	1.7	61.5
3	12.07	0.6	33.2	13.2	8.7	1.0	2.2	65.1
4	12.14	0.7	32.4	13.0	8.7	0.9	1.7	48.4
5	12.35	0.8	32.5	13.2	8.8	1.3	2.3	43.5
6	12.47	0.5	33.0	14.3	9.0	0.8	1.8	33.8
7	13.04	0.8	33.0	14.4	8.7	1.5	1.9	43.7
8	13.14	0.3	33.8	16.0	8.7	1.7	1.95	36.1

Table A.7 - Apozahualco Survey 17th July, 1976

		Physical Parameters				Chemical Parameters				Pigments	
Station	Time	Depth	Secchi Depth	Temp.	Salinity	pH.	Reactive Phosphate	Total Dissolved Phosphorus	Ammonia	CHL$_a$	Carot.
		m	m	°C	‰		µg at P l^{-1}		µg at N l^{-1}	mg/m^3	mg/m^3
1	18.05	0.70	-	31.0	32.75	8.12	0.76	1.25	3.0	0.5	0.33
2	18.14	0.70	0.50	34.2	30.5	7.9	0.84	1.36	1.2	2.26	2.0
3	18.20	1.00	bottom	33.4	29.3	8.0	1.06	1.50	2.0	0.93	1.8
4	18.25	1.00	bottom	33.7	29.1	8.0	1.14	1.76	1.6	1.6	1.4
5	18.30	1.00	0.80	34.0	25.5	8.0	0.97	1.34	2.5	1.2	2.7
6	18.35	0.70	0.40	35.0	24.4	7.9	1.03	1.47	1.7	7.7	3.7
7	18.50	0.80	0.40	33.6	25.1	8.0	1.08	1.55	2.0	2.4	2.5
8	18.55	0.60	0.40	34.0	25.8	8.0	1.08	1.69	-	3.2	3.3
sea	18.00	-	-	-	-	8.05	0.85	1.30	-	1.5	0.5

Table A 8 Apozahualco survey 11 September 1976

		Physical Parameters				Chemical Parameters			Pigments	
Station	Time	Depth	Secchi Depth	Temp.	Salinity	pH	Reactive Phosphate	Total Dissolved Phosphorus	CHL_a	Carot.
		m	m	°C	°/oo		µg at P l^{-1}		mg/m^3	mg/m^3
1 (S)	11.39	1.5	1.0	32.7	34.8	7.3	2.53	3.0	16.5	19.6
(1m)				31.3	35.8	-				
2	11.56	1.0	0.5	32.4	34.7	7.6	2.37	3.0	13.3	17.5
3	12.09	0.8	0.4	33.4	34.7	7.4	2.45	3.0	14.7	18.0
4	12.13	0.8	0.5	33.1	34.6	7.8	2.50	3.1	13.4	17.0
5	12.32	0.5	0.4	33.0	34.2	6.4	2.14	3.1	7.4	13.5
6	12.41	0.8	0.7	33.2	32.0	7.6	2.9	3.4	12.9	16.8
7	13.14	0.5	bottom	34.2	34.6	7.3	2.30	2.9	17.4	21.0
8	13.06	0.6	0.5	34.2	34.5	7.6	2.35	2.9	21.8	24.1

Station	Time	PHYSICAL PARAMETERS				CHEMICAL PARAMETERS			PIGMENTS	
		D̄epth	Secchi Depth	Temp.	Salinity	Reactive Phosphate	Total Phosporus	NH_4^+	Chl a	Carot.
		m	m	°C	°/oo	µg at P/1	µg at P/1	µg at N/1	mg /m^3	mg/m^3
1	13.42	0.60	bottom	32.6	33.1	0.7	1.02	1.3	-	-
2	13.25	0.70	bottom	32.9	32.0	0.64	1.05	0.6	4.6	4.7
3	13.00	0.70	bottom	32.3	32.6	0.75	1.12	0.2	4.1	4.7
4	14.10	0.75	bottom	32.8	31.5	0.71	1.13	1.1	-	-
5	14.30	0.70	bottom	33.3	30.9	0.83	1.14	1.4	-	-
6	14.40	0.35	bottom	35.0	30.9	1.00	1.40	1.9	6.1	6.1
7	14.55	0.70	0.50	34.4	31.5	0.86	1.35	1.2	-	-
Sea						0.65	0.92	0.9	0.9	1.0

Table A9 Apozahualco Survey 31 October 1976

60 minute exposure		30 minute exposure	
Depth m	Carbon fixed mg C m^{-3} hr^{-1}	Depth m	Carbon fixed mg C m^{-3} hr^{-1}
15.00 - 16.00		15.15 - 15.45	
0.0	377.6	0.0	374.4
0.5	131.6	0.5	67.4
1.5	8.1	1.5	-
18.25 - 19.25		18.40 - 19.10	
0.0	81.8	0.0	53.2
0.5	21.5	0.5	-
1.5	4.1	1.5	-
23.20 - 00.50			
0.0	0.0		
0.5	0.0		
07.00 - 08.00		07.15 - 07.45	
0.0	364.2	0.0	481.9
0.5	62.6	0.5	74.4
1.5	22.0	1.5	41.1
11.20 - 12.20		11.45 - 12.15	
0.0	502.3	0.0	382.2
0.5	236.1	0.5	210.0
1.5	19.7	1.5	41.5

Table P1 Productivity study Mitla 8 May 1976

60 minute exposure		30 minute exposure	
Starting time	Carbon fixed mg C m^{-3} hr^{-1}	Starting time	Carbon fixed mg C m^{-3} hr^{-1}
09.45	196.0	10.03	142.0
11.05	145.5	11.25	109.0
13.05	106.0	13.27	122.0
15.13	47.0	15.27	71.2
17.00	21.8	17.17	11.9

Table P2 Productivity study Chautengo 11 May 1976

Depth m	Carbon fixed mg C m^{-3} hr^{-1}	Depth m	Carbon fixed mg C m^{-3} hr^{-1}
07.50 - 08.50		13.33 - 14.33	
0.0	77.2	0.0	259.8
0.75	2.1	0.75	59.9
1.5	-	1.5	8.8
09.44 - 10.44		15.42 - 16.42	
0.0	191.8	0.0	336.1
0.75	25.7	0.75	83.6
1.5	4.5	1.5	13.1
11.32 - 12.32		17.32 - 18.32	
0.0	307.5	0.0	102.7
0.75	55.1	0.75	10.6
1.5	20.8	1.5	1.9

Table P3 Productivity study Chautengo 26 June 1976

Time	Depth m	Carbon fixed mg C m^{-3} hr^{-1}
09.00 - 10.00	0.0	25.2
	0.75	26.2
11.00 - 12.00	0.0	23.5
	0.75	24.3
13.04 - 14.06	0.0	34.5
	0.75	34.2
15.03 - 16.03	0.0	24.9
	0.75	34.3
17.17 - 18.17	0.0	15.36
	0.75	7.55

Table P4 Productivity study Chautengo 19 July 1976

Time	Depth m	Carbon fixed mg C m^{-3} hr^{-1}
09.40 - 10.40	0.0	105.3
	1.0	82.5
11.50 - 12.55	0.0	64.0
	1.0	77.2
13.55 - 14.55	0.0	45.5
	1.0	83.3
17.15 - 18.15	0.0	34.5
	1.0	0.0.35

Table P5 Productivity study Chautengo 10 September 1976

Depth m	Carbon fixed mg C m^{-3} hr^{-3}	Depth m	Carbon fixed mg C m^{-3} hr^{-1}
18.30 - 19.30		11.15 - 12.15	
0.0	19.9	0.0	328.0
0.3	13.7	0.3	309.0
1.0	0.0	1.0	12.2
0.700 - 08.00		13.05 - 14.05	
0.0	654.0	0.0	376.0
0.3	110.0	0.3	595.0
1.0	0.0	1.0	16.0
09.00 - 10.00		16.00 - 17.00	
0.0	386.3	0.0	479.0
0.3	350.0	0.3	398.0
1.0	8.4	1.0	0.0

Table P6 Productivity study Mitla 9 September 1976.

Depth m	Carbon fixed mg C m^{-3} hr^{-1}	Depth m	Carbon fixed mg C m^{-3} hr^{-1}
16.45 - 17.45		10.53 - 12.17	
0.0	44.5	0.0	359.6
0.5	2.3	0.5	67.0
		1.0	-
08.03 - 09.03		13.25 - 14.25	
0.0	350.0	0.0	370.2
0.5	57.4	0.5	57.1
1.0	6.7	1.0	13.3

Table P7 Productivity Study Mitla 4 - 5 November 1976

Depth m	Carbon fixed mg C m^{-3} hr^{-1}	Depth m	Carbon fixed mg C m^{-3} hr^{-1}
<u>07.37 - 08.37</u>		<u>14.33 - 15.33</u>	
0.0	330.	0.0	280.
0.5	111.	0.5	296.
1.0	11.6	1.0	11.0
<u>10.42 - 11.42</u>		<u>16.02 - 17.02</u>	
0.0	271.	0.0	426.
0.5	427.	0.5	135.
1.0	47.	1.0	12.
<u>12.37 - 13.37</u>			
0.0	401.		
0.5	509.		
1.0	91.		

Table P8 Productivity study Mitla 9 December 1976

Time	Depth m	Carbon fixed mg C m^{-3} hr^{-1}
06.45 - 07.45	0.0	32.5
	1.0	4.6
10.55 - 11.55	0.0	10.8
	1.0	25.2
13.25 - 14.45	0.0	17.7
	1.0	24.9
15.32 - 16.35	0.0	37.1
	1.0	32.7
17.25 - 18.25	0.0	1.7
	1.0	0.2

Table P9 Productivity study Chautengo 11 December 1976

Time	Depth m	Temp. °C	Oxygen ml l^{-1}	Time	Depth m	Temp. °C	Oxygen ml l^{-1}
16.16	0.0	29.0	7.6	04.45	0.0	28.1	4.5
	1.0	28.5	7.2		1.0	27.7	4.6
	2.0	28.4	6.4		2.0	27.7	4.3
	3.5	27.5	0.3		3.5	27.5	0.13
21.15	0.0	28.5	6.5	08.00	0.0	27.9	2.4
	1.0	28.3	6.8		1.0	27.7	2.9
	2.0	28.2	-		2.0	27.7	1.7
	3.5	27.5	0.0		3.5	27.5	0.0
23.35	0.0	28.4	-	10.15	0.0	27.9	3.9
	1.0	28.4	6.4		1.0	27.9	3.2
	2.0	28.3	6.5		2.0	27.7	1.3
	3.5	27.6	0.0		3.5	27.4	0.0
01.30	0.0	28.5	5.8	13.30	0.0	28.7	4.6
	1.0	28.1	6.0		1.0	28.5	4.1
	2.0	27.9	4.5		2.0	28.4	3.1
	3.5	27.4	0.0		3.5	28.1	1.9

Table M1 24 hour temperature and oxygen study Mitla
19 January 1976

Time	Depth m	Temp. °C	O_2 ppm	Reactive P µg atP 1^{-1}	NH_4^+ µg at N 1^{-1}
13.30	0.0	31.6	9.3	0.37	1.3
	0.5	31.4	8.8	0.37	0.6
	1.5	31.1	8.2	0.40	0.7
	3.0	30.3	7.7	0.39	1.4
	4.0	30.0	3.4	0.39	1.5
17.10	0.0	31.5	11.0	0.39	0.9
	0.5	31.5	11.0	0.37	1.0
	1.5	31.4	10.7	0.40	1.2
	3.0	29.6	0.26	0.38	1.3
	4.0	29.6	<0.50	0.42	2.7
21.30	0.0	30.9	10.9	0.41	1.0
	0.5	31.0	10.8	0.37	1.0
	1.5	31.1	10.7	0.37	0.7
	3.0	30.0	0.7	0.39	1.4
	4.0	29.7	0.2	0.37	0.7
02.00	0.0	30.3	8.3	0.39	0.7
	0.5	30.5	7.9	0.39	0.7
	1.5	30.5	7.9	0.36	0.7
	3.0	29.8	0.15	0.38	0.8
	4.0	29.5	<0.1	0.38	35.0

Time	Depth m	Temp. °C	O_2 ppm	Reactive P µg at P 1^{-1}	NH_4^+ µg at N 1^{-1}
05.15	0.0	30.0	6.2	0.37	1.3
	0.5	30.0	6.0	0.37	0.7
	1.5	30.2	5.7	0.36	0.6
	3.0	29.8	0.2	0.38	0.7
	4.0	29.6	<0.1	0.44	26.0
09.20	0.0	30.6	8.4	0.39	0.6
	0.5	30.3	7.8	0.37	1.5
	1.5	30.1	4.8	0.40	0.4
	3.0	29.7	0.2	0.39	1.6
	4.0	29.7	<0.1	0.48	38.4
11.20	0.0	-	8.7	-	-
	0.5	-	8.7	-	-
	1.5	-	6.4	-	-
	3.0	-	2.6	-	-

		Chl a mg m^{-3}	Carot mg m^{-3}	pH
09.20	0.0	144	171	8.9
	0.5	148	178	8.7
	1.5	156	166	8.9
	3.0	153	165	8.7
	4.0	-	-	-

Table M2 24 hour study Mitla 8 May 1976

Station	Carbonate % $CaCO_3$	Total Phosphorus ppt	Insoluble Carbon %	Insoluble Nitrogen %
1	36.9	7.8	2.9	0.30
2	4.2	8.5	3.6	0.34
3	21.9	7.8	3.8	0.47
4	7.0	5.5	2.3	0.30
5	42.2	7.7	3.5	0.42
6	6.6	3.9	2.0	<0.2
7	2.2	9.3	4.6	0.49
8	5.1	10.9	4.3	0.42
9	9.8	8.7	3.8	0.48
10	3.1	8.8	3.6	<0.2
11	7.5	8.9	3.4	<0.2
12	8.3	6.9	2.4	<0.2
13	0.4	6.7	3.5	0.28
14	-	-	-	-
15	9.9	4.8	2.1	0.22
16	0.4	3.4	1.9	<0.2
17	0.9	2.7	1.9	<0.2
18	-	-	--	-
19	5.7	16.5	3.2	0.31

Table S1 General sediment analyses - Chautengo surface sediments

Table 5.2 - Analyses of sediment cores, Mitla

Core	Depth	Sediment Analyses				Interstitial Water			
		Water Content	Carbonate	C	N	PO_4	NH_4^+	pH	Salinity
	cm	%	%	% Dry Weight	% Dry Weight	µg/g.sed	µg/g.sed		‰
1	0-10	-	-	-	-	-	-	-	-
	10-20	89.5	-	18.3	2.1	2.72	15.7		
	20-30	91.0	-	20.6	2.3	1.87	17.3		
	30-40	93.0	3.0	12.2	1.44	1.46	15.9		
	40-50	75.0	3.3	5.2	0.49	1.04	11.1		
	50-60	65.0	12.7	6.5	0.57	0.84	12.1		
	60-70	67.0	17.9	8.32	0.46	0.87	8.8		
	70-85	59.0	51.8	9.32	0.59	0.46	7.6		
2	0-10	82.5	-	17.4	2.15	7.2	16.7		
	10-20	-	-	-	-				
	20-30	87.0	-	19.3	1.95	3.47	28.7		
	30-40	89.0	-	18.9	2.06	3.25	32.1		
	40-50	91.0	4.5	23.2	2.48	3.78	50.0		
	50-60	83.0	4.3	15.7	1.64	3.66	37.4		
	60-70	74.5	5.7	8.52	0.86	3.32	31.9		
	70-80	74.0	6.6	9.01	0.82	3.35	38.0		
	80-90	77.0	6.8	10.9	1.02	3.47	37.7		
3	0-10			16.2	1.78	2.94	27.1	7.5	3
	10-20			19.6	2.10	5.11	52.3	7.1	3
	20-30	average		22.5	2.40	6.69	63.4	7.3	5
	30-40	85		24.1	2.69	6.95	54.8	7.9	8
	40-50			28.3	2.92	6.77	82.4	7.9	9
	50-60			27.9	3.10	7.29	78.7	7.8	9
	60-70			24.4	3.01	7.11	82.6	7.8	8
	70-80			-	-	7.51	93.2	7.8	9
	80-90			18.3	1.98	6.93	93.9	7.9	-

APPENDIX 2

The use of the oxygen method in assessing primary production in coastal lagoons.

Gross primary production and respiration can be estimated conveniently by the method of Odum (Odum 1960; Odum & Wilson 1962; Odum et al 1963). This, in common with all methods for productivity measurement, is based on the equation for photosynthesis

$$CO_2 + H_2O \overset{h\nu}{\rightleftarrows} (CH_2O) + O_2 \quad .$$

The rate of oxygen production should thus be directly proportional to the rate of formation of organic material.

Changes in the observed concentration of oxygen at a particular point can be expressed thus,

$$\frac{\partial [O_2]}{\partial t} = P - R + D \quad , \qquad (1)$$

where P, R an D represent the contributions due to productivity, respiration and diffusion respectively.

In order to use this equation to assess productivity and respiration from observations of oxygen concentration, it is necessary to make a number of simplifying assumptions :-

1) the term R remains constant over the period of measurement,
2) the water column is completely mixed,
3) the diffusion term represents the transfer of oxygen to or from the atmosphere,
4) the magnitude and direction of oxygen diffusion is linearly dependent on the extent of saturation of the water.

The value of D is then given by

$$D = \frac{K\ (100 - S)}{100} \quad , \qquad (2)$$

where K is a diffusion coefficient (assumed constant) and S is the calculated percentage saturation. The diffusion coefficient (K) may be estimated from two values of $(\partial[O_2] / \partial t)$, measured during the night (when P is zero). As R is assumed to be constant, the difference between these values may be expressed as

$$\left(\frac{\partial [O_2]}{\partial t}\right)_1 - \left(\frac{\partial [O_2]}{\partial t}\right)_2 = D_1 - D_2 = \frac{K\,(S_2 - S_1)}{100} \qquad (3)$$

In order to reduce the error on the estimate of K, the term $S_2 - S_1$ should be as large as possible. This can usually be achieved by utilizing measurements made just before dawn (subscript M) and just after dusk (subscript E). A value for K is then given by

$$K = \frac{100\left(\frac{\partial[O_2]}{\partial t}\right)_M - \left(\frac{\partial[O_2]}{\partial t}\right)_E}{(S_E - S_M)} \qquad (4)$$

Once a value of K has been obtained, the value of D can be calculated for any observation by the use of equation 2.

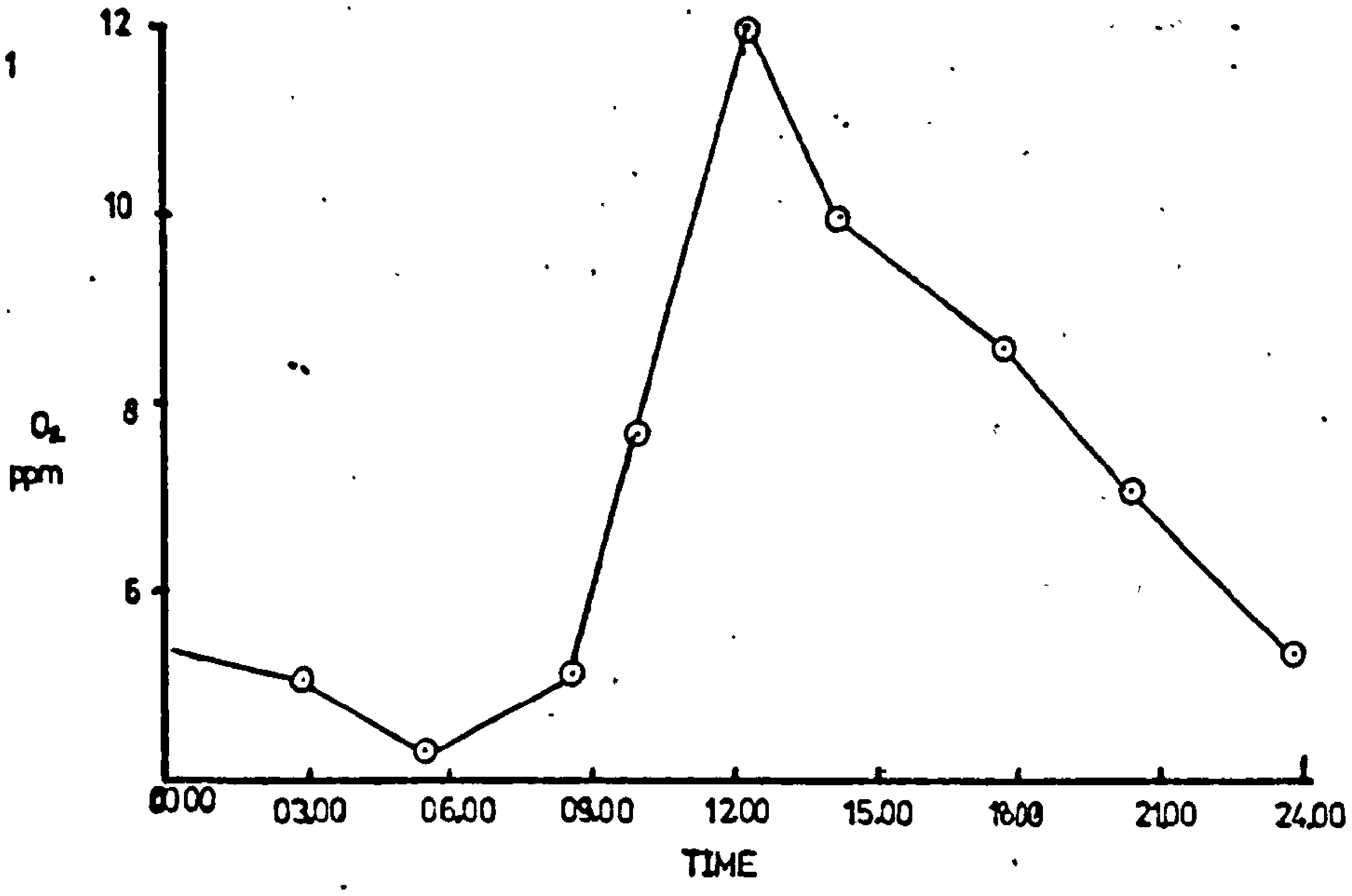
A typical calculation is illustrated by figure A2.1 . The data consists of a series of measurements of oxygen, temperature and salinity over a twenty-four hour period at a station away from any strong currents. The average oxygen concentrations (plot 1) were used to calculate the corresponding percentage saturation of oxygen (plot 2). The value of P - R was then calculated :

$$(P - R) = \frac{\Delta [O_2]}{\Delta t} - \frac{K\,(100 - S)}{100} \qquad (5)$$

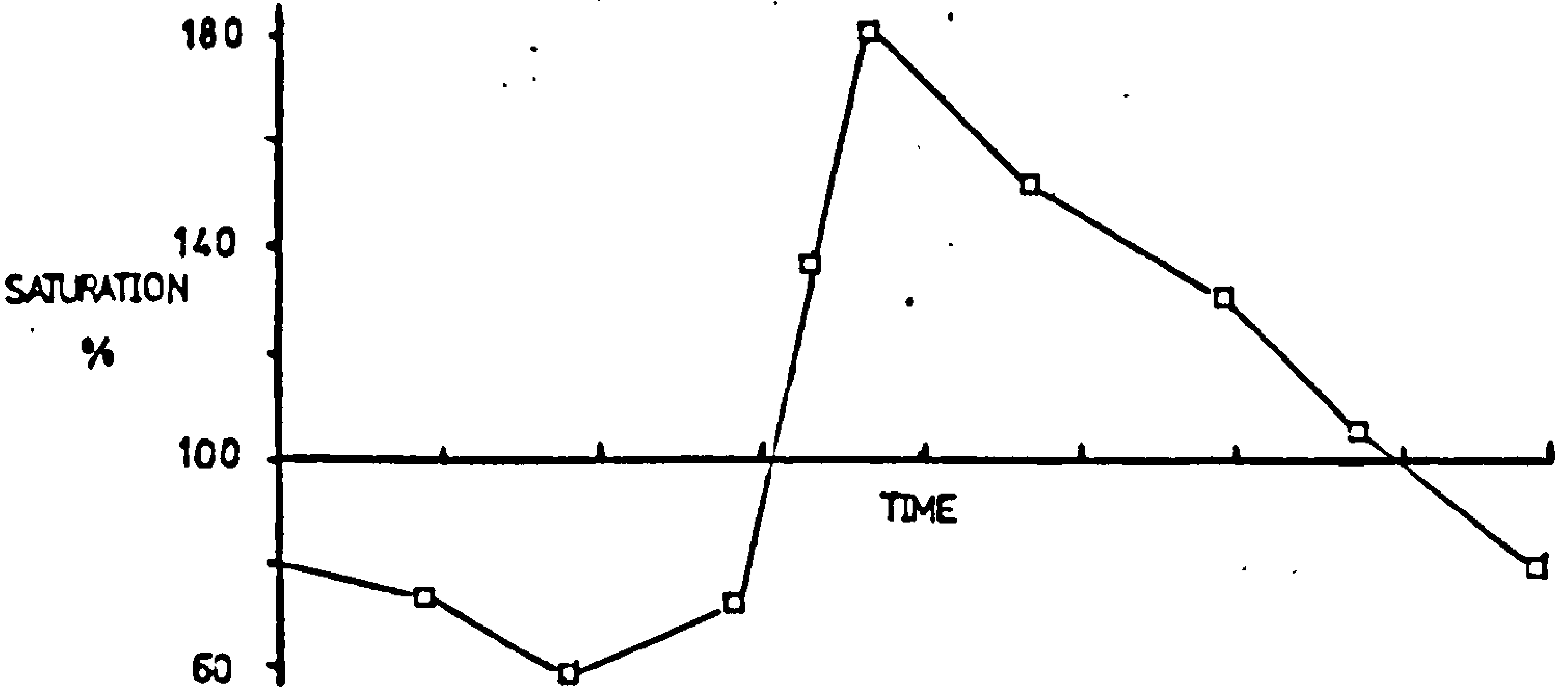
If R is constant (assumption 1), the night-time value of (P - R) should be constant and equal to -R . This is shown to be nearly the

Figure A.1
LAGUNA CHAUTENGO
ESTIMATION OF PRIMARY PRODUCTIVITY
(STATION 3)
APRIL 1976

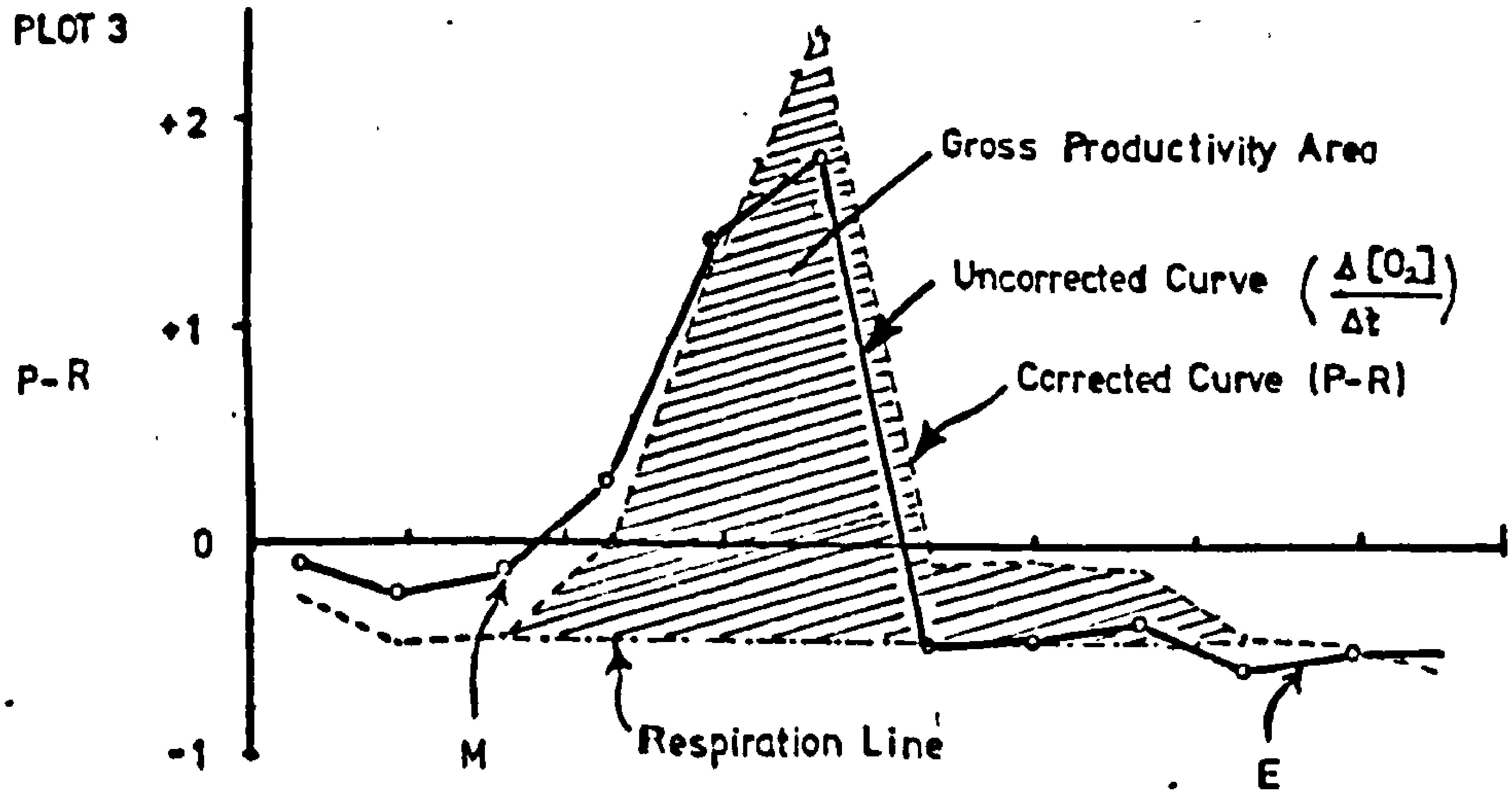
PLOT 1



PLOT 2



PLOT 3



case for this example. This value of R can thus be used for the day-time period (the 'respiration line' in plot 3). The shaded area in plot 3 then represents the gross productivity.

Unfortunately, under certain circumstances the value of R does not appear to be constant. The example shown in the text (fig 6.18) illustrates a case where the total oxygen demand severely reduces the amount of oxygen available for respiration and thus the magnitude of R decreases. In such situations, assignment of a value to R constitutes little more than an educated guess.

The presence of an appreciable variation of oxygen concentration with depth indicates that the water column is not completely mixed (i.e. assumption 2 is invalid). The estimation of productivity then requires further assumptions. In his original paper, Odum suggested the use of an average oxygen concentration for the water column. Unfortunately, if the concentration gradient is large, the amount of diffusion calculated from this average value may be seriously in error. The exchange of oxygen with the atmosphere must be controlled by the oxygen saturation in the surface layer. If the observed oxygen profile shows the presence of distinct homogenous layers, an improved estimate of the productivity can be made. This is achieved by considering the layers as separate, and assuming that there is no net oxygen diffusion from the surface layer to the subsurface layers. An average value for the productivity can then be calculated from the expression

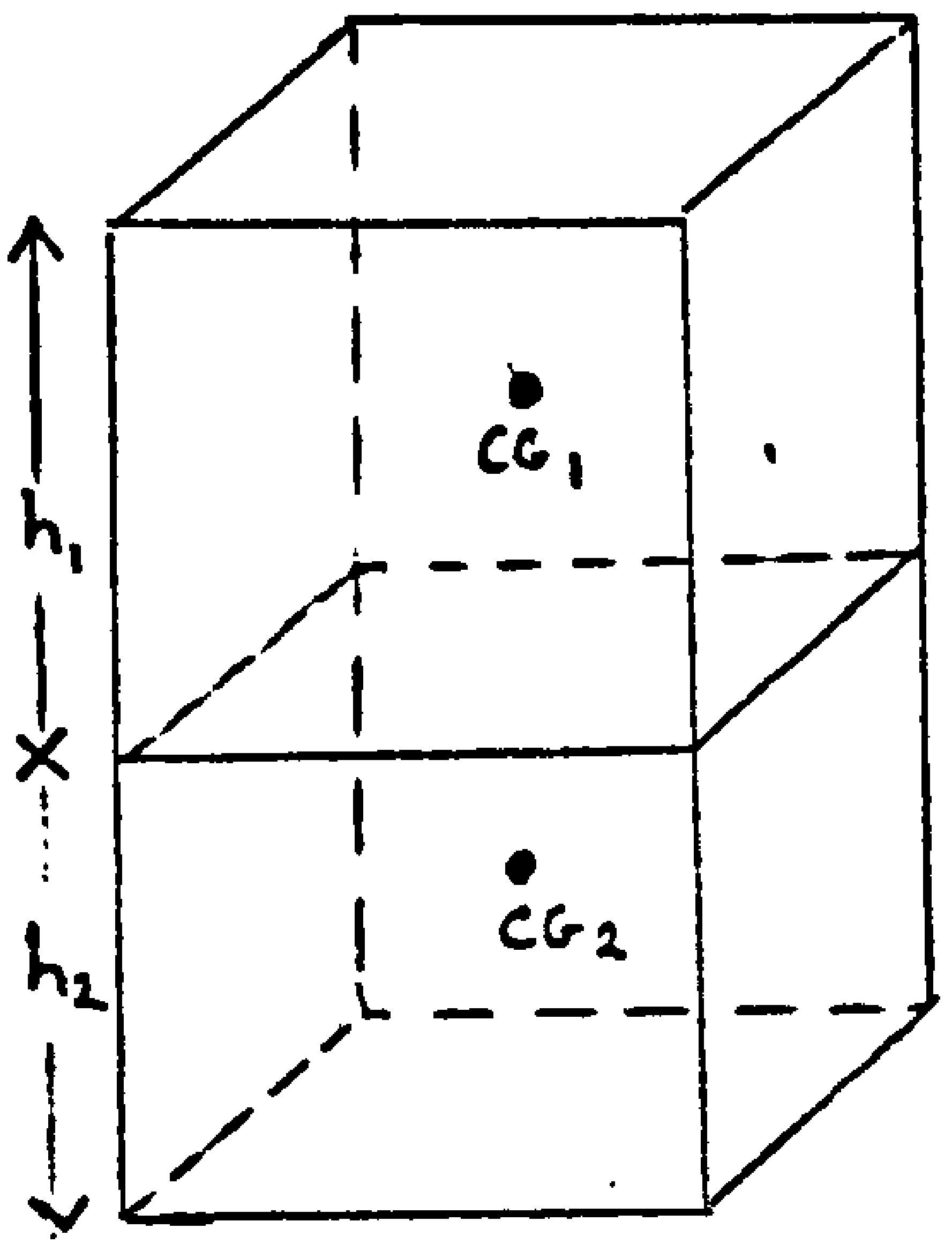
$$\left(\frac{\Delta [O_2]}{\Delta t}\right) = P - R + \frac{d}{z} D_{\text{surface layer}} , \qquad (6)$$

wher d is the depth of the surface layer and z is the total depth.

In the majority of cases where this modification was applied (Laguna Mitla), the contribution of diffusion to the amount of oxygen in the system was found to be fairly small. In these cases, the contribution would have been assessed as much larger using the method of Odum.

APPENDIX 3

The method for calculating the energy required to mix a stratified water column considers change in potential energy (P) in mixing water layers 1 and 2 of thickness h_1 and h_2 and specific gravity δ_1 and δ_2 respectively. The surface area of the water column is chosen as unity.



The masses of water (m_1 and m_2) are thus:

$$m_1 = \delta_1 h_1$$
$$m_2 = \delta_2 h_2 ,$$

and their potential energies (above the lagoon floor) are

$$P_1 = g\,\delta_1 h_1 \left(h_2 + \frac{h}{2}1\right)$$
$$P_2 = g\,\delta_2\, h_2^2 / 2 .$$

If the water mixes

$$m_1 + m_2 = \delta_1 h_1 + \delta_2 h_2$$
$$\delta\,(\mathrm{mix}) = \frac{\delta_1 h_1 + \delta_2 h_2}{h_1 + h_2}$$

$$P(\mathrm{mix}) = g\,(\delta_1 h_1 + \delta_2 h_2)\,(h_1 + h_2)/2 .$$

The change in potential energy of the system on mixing is given by

$$\Delta P = P(\mathrm{mix}) - (P_1 + P_2) .$$

Hence

$$\Delta P = g\,(\delta_1 h_1 + \delta_2 h_2)(h_1 + h_2)/2$$
$$- (\delta_1 h_1 \,(h_2 + h_1/2) + \delta_2 h_2^2/2) \qquad (1)$$

However, if h_1 is chosen to be equal to h_2

$$\Delta P = g h^2(\delta_2 - \delta_1)/2 \quad , \qquad (2)$$

where ΔP is the energy required to mix the two halves of the water column. Values of δ are computed from Knudsen's Tables and are converted to S.I. units. The value of ΔP may be calculated from either expression 1 or 2.